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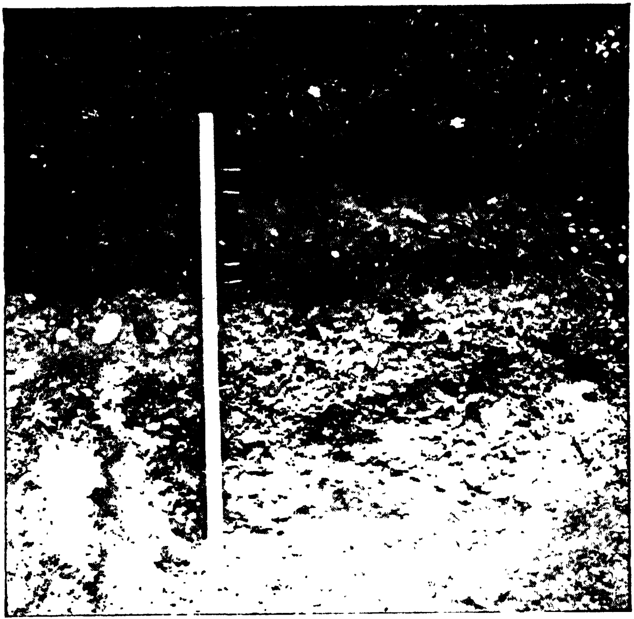
THE SOIL

ALSO BY SIR A. D. HALL

FERTILIZERS AND MANURES

THE FEEDING OF CROPS AND STOCK

AGRICULTURE AFTER THE WAR



[*Photo. W. Morley Davies.*

Podsol Soil Profile. Goldstone Common, Newport, Salop.

THE SOIL

An Introduction to the Scientific Study of the Growth of Crops

* * *

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INVESTIGATION OF THE SOIL

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INTRODUCTION TO THE ORIGINAL EDITION

THE study of the soil, which is fundamental in any application of science to that part of agriculture which deals with the growth of crops, has received greatly increased attention during the past few years. The crude chemical point of view, which in the main regarded the soil as a nutritive medium for the plant, has been altogether extended, by a consideration of the soil as the seat of a number of physical processes affecting the supply of heat and of air and water to the plant, and again as a complex laboratory, peopled by many types of lower organisms, whose function is in some cases indispensable, in others noxious, to the higher plants with which the farmer is concerned. These three kinds of reaction—chemical, physical, and biological—interact upon one another and upon the crop in many ways; they are affected by, and serve to explain, the various tillage operations which have been learnt by the accumulated experience of the farming community, and the hope for future progress lies in the further adaptation for practical ends of these processes at work in the soil. But it must not be supposed that science is yet in a position to reform the procedure of farming, or even to effect an immediate increase in the productivity of the land: agriculture is the oldest and most widespread art the world has known, the application of scientific method to it is very much an affair of the day before yesterday. Nor can we see our way to any radical acceleration of the turnover of agricultural operations that shall be economical; the seasons and the vital processes of the living organism are stubborn facts, unshapable as yet by man with all his novel powers. But even if the best farming practice is still a step beyond its complete explanation by science, yet the most practical man will find his perception stimulated and his power of dealing with an emergency quickened by an appreciation of the reasons underlying the tradition in which he has been trained ; and such an introduction to the knowledge of the soil it is the aim of this little book to supply. The book is primarily intended for the students of our agricultural colleges and schools, and for the farmer who wishes to know something about the materials he is handling day by day. While a certain knowledge of chemistry is assumed, it is hoped that the subject is so treated as to be intelligible to the non-technical reader who is without this preliminary grounding. Though the book is in no sense an exhaustive treatise, it has been my desire to give the reader an outline of all the recent investigations which have opened up so many soil problems and thrown new light on difficulties that are experienced in practice. The scope of the book precludes the giving of references and authorities for all the statements which are made ; but, for the sake of the more advanced student, a bibliography has been appended, which will take him to the original sources and give him the means of learning both sides of the more controversial questions.

The same reason—want of space—has prevented me from giving an adequate justification of some of the points of view indicated. Any worker in so novel and unsurveyed a field as the study of the soil still presents, must arrive at certain personal conclusions, and I have tried to steer a middle course between an over insistence on these points on the one hand, and the colourlessness that would come from their entire exclusion on the other. No great part of a text-book can pretend to be original, but in the sections dealing with the chemical analysis and the physics of the soil, I have incorporated a good many unpublished measurements and observations ; for the mass of the results on which the book is based, I am chiefly indebted to the work of Lawes and Gilbert, as set out in the *Rothamsted Memoirs*, and to the writings of Warington in this country, of King, Hilgard, and Whitney in America, of Wollny in Munich.

I have to thank Professor J. Percival, of the South-Eastern Agricultural College, for notes respecting the association of plants with specific soils, and many suggestions on biological questions; Major Hanbury Brown, C.M.G., head of the Egyptian Irrigation Department, for information concerning "salted" lands in Egypt; Mr. F. J. Plymen, who has been associated with me in carrying out a soil survey of the counties of Kent and Surrey, and has executed many of the observations recorded here; Mr. W. H. Aston, one of my pupils, to whom I owe the observations on page 117; and finally, Dr. J. A. Voelcker, to whom I am greatly indebted for reading the proof-sheets, and making valuable suggestions thereon.

A. D. HALL.

HARPENDEN, *December* 1902.

PREFACE TO THE FIFTH EDITION

THE revision of such a classic of the soil as Sir Daniel Hall's *The Soil* is no light task. My aim has been to preserve as far as possible the general character of the work and to cater for the same class of readers as that for which Sir Daniel Hall wrote with such success.

The Soil was published originally in 1903. Since that time there have been great advances in our knowledge of the soil. The subject has, indeed, ceased to be a branch of agricultural chemistry and has become a branch of natural science comparable with geology or botany. In the successive revisions of the book, Sir Daniel Hall embodied, so far as was possible within the original framework, the more important advances in the subject. Since the last revision in 1931, however, important developments have taken place and when I first considered the present revision, it became evident that something more was required than the mere embodiment of additional material. I have therefore tried—not to my own complete satisfaction—to re-cast the whole book and, whilst preserving as much as possible of Sir Daniel Hall's work, to give a re-statement of the subject as it appears in 1944. This has involved the omission of a considerable amount of material and the insertion of new material.

Chapter I (Origin of Soils) has been considerably modified to form Chapter II of the new edition. Chapter II (Mechanical Analysis of Soils) has been replaced by Chapter III on the Proximate Composition of Soils. Part of Chapter III (Tillage and Water Movements in Soils) has been embodied in the new Chapter IV on Structure and Tillage Properties of Soils. Chapter V on Soil Moisture is mainly new, but includes some material from the old Chapters III and IV. Chapters V (Temperature of the Soil) and VII (Living Organisms of the Soil) appear almost unchanged as Chapters VI and VIII, respectively. Chapter VIII (The Power of the Soil to Absorb Salts) has been replaced by Chapter VII on the Chemistry of Soils. Chapter IX (Fertility and Sterility of Soils) has been largely re-written. Chapter X (Soil Types) has been replaced by Chapter X on the Classification and Mapping of Soils. Finally, Chapter VI (Analysis of Soils) has been put last as Chapter XI, and has been re-written, omitting details of actual methods, which are more appropriately found in standard works on soil analysis.

Although every effort has been made to assimilate the new material to that of Sir Daniel Hall, the work is a conflation and as such must necessarily offer opportunities for the textual critic to discover cases of " unconformity " and " overlap." The revision, carried out under the stress of wartime conditions, is necessarily of " utility " standard and lacks the polish that might be expected of a revision made in more spacious days. I venture to hope that there will be an opportunity to remedy the grosser defects and omissions in a subsequent edition.

G. W. ROBINSON.
BANGOR, *October* 1944.

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CHAPTER I

INTRODUCTORY

In the Scientific Study of Soils, Chemical, Physical, and Biological Considerations are involved—Soil Material—Soil Profile.

THE whole business of agriculture is founded upon the soil ; for the soil the farmer pays rent, and upon his skill in making use of its inherent capacities depends the return he gets for his crops. Taking rent as a rough measure of the productive value of land, it is clear that enormous differences must exist in the nature of the soil, for in the same district some land may be rented at £2, and other land at as little as 5s. per acre. Of course, rent is not wholly determined by the nature of the soil, but depends also on the proximity of a market and the adaptability of the land to special purposes ; a light sandy or gravelly soil, almost worthless for general agricultural purposes, may be valuable in the neighbourhood of a large town, because its earliness and responsiveness to manure make it specially suitable for market gardening.

In some cases the difference between soils is seen in the quality of the crop produced rather than in the productiveness ; for example, the " red lands " of Dunbar are famous for the high quality of the potatoes grown upon them : such potatoes will sell at 80s. to 90s. per ton, when potatoes grown upon the Lincoln warp soils are at 60s., and those from the black soils of the fen country are only fetching 45s. to 50s. This extra price for the red land potatoes is due to the fact that they can be cooked a second time, after cooling, without changing colour, whereas the ordinary potato is apt to blacken a little when once cooked and allowed to grow cold.

The scientific study of soils is concerned with the differences indicated above ; its endeavour is to obtain such a knowledge of the constitution of the soil and the part it plays in the nutrition of the plant, as will make clear the cause of the inferiority of any given piece of land, and ultimately enable the farmer to correct it. The problems involved are far more complex than they appear ; at first sight nothing would seem easier than to make a chemical analysis of the soil and find out in what respects it differs from another soil of known value ; then the deficiencies or the excesses, as compared with the good soil, could be corrected by suitable manuring. The matter is not, however, quite so simple, for if on the one hand the soil can be considered as a great reservoir of plant food that can be recovered in crops, on the other hand it is equally correct to regard the soil as a manufactory, a medium for transforming raw material in the shape of manure into the finished article—the crop. In new countries where virgin soil is being exploited, and in districts where the systems of agriculture are primitive, the former point of view is the correct one ; nothing is given to the soil beyond that amount of labour that will enable some of its inherent value to be realized in a crop. Little by little the capital, which may be practically boundless, as in the great wheat lands of Manitoba, or initially little enough, as on a Connemara heath, is being drawn upon and not replaced. But in a Kentish hop-garden or other land where an intensive system of cultivation is practised, the crop does not remove as much as it receives ; often the land is intrinsically poor and owes its value to the manner in which it will elaborate the raw material supplied as manure. And not only are these very special soils gaining, rather than losing fertility with each crop, but, from a general point of view, all countries that are being highly farmed, like parts of Great Britain, are steadily increasing in fertility at the expense of other countries that are growing crops on virgin soil ; in the linseed, the maize, the cotton seed, that are fed to our stock, there travels to our soil some of the wealth of the lands upon which these crops were grown. Hence the study of the inherent resources of the soil is perhaps less important than an examination of the manner in which the soil deals with such materials supplied under cultivation.

A clear distinction must be made at the outset between soil as *material* and soil as a *natural body* or *individual.* When we study soil as material, we try to find out how the complex substance is made up and to learn something of its physical and chemical properties. But even if we have succeeded in this enquiry, we are still far from understanding the soil as it occurs in the field or the forest and as it is related to the growth of crops and trees. Thus we are led to study soils as individuals. We thus distinguish *soil,* the material, and *a soil,* which is a natural body. The difference in approach is analogous to the difference between studying plant or animal materials and studying plants and animals as living individuals.

What, then, do we understand by the soil as an individual? we open up a trench or cutting in a soil, we see a stratified arrangement of soil and subsoil layers, passing down to the raw material, gravel, sand, clay, or weathered rock, from which the soil has been derived. The succession of layers or *horizons* down to the raw parent material is called the *soil profile.* This is the soil individual and this is our ultimate object of study and our unit of classification. Much of the earlier failure to apply the study of the soil to the service of practical agriculture has been due to our looking at the soil as so much laboratory material, rather than trying to understand the behaviour of the soil in the field. We are only now beginning to realize the implications of this new outlook.

Although we must ultimately attempt a synthesis of our knowledge in terms of soils as individuals, much of the preliminary study of the soil must have to do with soil as material; just as the materials of the human body must be studied in order to understand the anatomy, physiology, and psychology of human beings.

The complete knowledge of the soil and the part it plays in the nutrition of the plant requires investigation along three lines, which may be roughly classed as—chemical, physical or mechanical, and biological; naturally these points of view are not independent of one another, but are only so separated for convenience of study.

In the first place, we know that the plant derives certain substances necessary to its development from the soil: nitrogen and all the ash constituents reach the plant in this manner. We have, therefore, to investigate the proportions in which these constituents are present in the soil, the state of combination in which they may respectively exist, and the variations in these factors normally exhibited by typical soils, all of which questions may be described under the head of chemical analysis. Further investigations of a chemical nature deal with the power of various soils to retain manure, the causes of sterility or fertility, and the measures that can be adopted for the amelioration of soils.

The soil is, however, not merely a storehouse of food for the plant, since water is equally indispensable to its existence and is immediately derived from the soil through the plant roots; hence it is of prime importance to study the causes that underlie the movement of water in the land, and its supply to the growing crop. In the relation between soil and water the cultivation to which the land is subjected plays a prime part, hence it will be necessary to trace the effect of each of the main operations of tillage upon the structure of the soil. Again, the texture of the soil and the proportions of water and air it retains, affect its temperature and that responsiveness to change of season which we roughly indicate by the terms " early " and " late " soils. The general consideration of these questions may be termed soil physics.

Finally, the soil is not a dead mass, receiving on the one hand manure, which it yields again to the crop by purely mechanical or chemical processes; it is rather a busy and complex laboratory where a multitude of minute organisms are always at work. By the action of some of these organisms, vegetable residues and manures are brought, we might almost say digested, to a condition in which they will serve as food for plants; others are capable of bringing into combination, or " fixing," the free nitrogen gas of the atmosphere, and therefore add directly to the capital of the soil; others again are noxious or destructive to the food stores in the soil.

The work of these organisms is much affected by cultivation; in fact, it would not be too much to say that most of the operations upon the farm have received a new light from the knowledge that has been acquired in the last few years of the living processes taking place in the soil. In this direction also new developments of agriculture may prove to be possible, and though the progress is only small as yet, we see indications that the productive capacity of the land may be increased by the introduction of certain organisms capable of assisting the work of the higher plants or by the destruction of others that limit the development of the useful organisms.

On the biological side we have also to study the association of certain plants with particular soils ; an examination of the natural flora of any district will show that some species are almost confined to sandy soils, others to soils containing chalk, rarely wandering on to different types of soil ; again, particular weeds are characteristic of clay land, others of sand ; and some even of our cultivated crops show a marked intolerance for particular soils.

The full story of the soil cannot yet be told ; small wonder that in the course of many centuries man has been cultivating the face of the earth, he has found out much that science can barely explain, still less improve upon. Nor are the problems simple—the food, the water, the temperature, the living organisms in the soil are all variables, affected by cultivation and climate, themselves also variable ; they all act and react upon one another and upon the crops ; hence we can easily understand that the smallest farm may present problems beyond the furthest stretch of our knowledge.

CHAPTER II

THE ORIGIN OF SOILS

Stages in Soil Formation: Weathering and Profile Development—Sedentary and Transported Soils—Rock-forming Minerals—Mechanical Weathering—Chemical Weathering—Biological Weathering—Soil Formation: Organic Matter Profile; Eluviation—Human Interference as a Soil-forming Factor—Soil and Subsoil.

THE study of soils must begin with some knowledge of their origin and their relationship to the rocks from which they are ultimately derived. It is convenient to consider the development of soil from rock as taking place in two stages, namely, rock weathering and soil profile development. The product of the processes of rock weathering is the parent material of the soil.

Sedentary and Transported Soils

Perhaps the best way of arriving at an idea of the natural processes which result in soil is to visit a river valley and examine, first a quarry on the flanks of the hills, and then one of the cuttings for gravel or brick-earth, which often lie a little above the river level.

The face of the quarry shows at a depth of 10 feet or so from the surface the massive rock, unaltered as yet by the action of weather. Closer examination, however, shows that even at this depth the rock is not quite solid; if it be a stratified rock the planes of bedding are apparent, along which the rock can be split. Joints again traverse the rock at right angles to the bedding planes, and along both joints and bedding planes it is evident that water makes its way, for the edges of the cracks are slightly altered and discoloured. Nearer the surface, the cracks and lines of weakness in the rock become more palpable; in some cases the joints have been forced open by the intrusion of the roots of trees; minor cracks have started from the main ones, and the disintegration of the rock at the edges of the cracks has proceeded further, till at a distance of 3 or 4 feet from the surface the whole material is loose and shattery, though still preserving the appearance of solid rock. Still nearer the surface the rock structure seems to have disappeared ; rock may be there in lumps and fragments, but it is embedded in small material which we may regard as the parent material of the soil. Again nearer the surface the rock fragments become smaller and the proportion of fine earth larger, till in the top 9 inches or so a new change begins. Here the stones are generally small, and the material is dark from the admixture of *humus*, the complex material formed from the decomposition of the residues of crops and vegetation that have covered the surface in past years. These upper horizons form the actual soil profile, which we may for the present consider as the soil proper, underlain and shading into the subsoil, which in its turn passes gradually into the parent material, which is derived from and itself passes into the undecomposed rock

If the soil is in cultivation, the surface soil down to tillage depth is generally uniform in character ; but the subsoil may often be seen to be subdivided into a number of distinct layers or horizons. Under natural vegetation, such as forest or prairie, distinct horizons may be observed also in the surface soil. The succession of horizons in soil and subsoil is termed the *soil profile*, and is the unit of study when the soil is considered as an individual. In the case we are considering, there is a gradual transition through the soil horizons, through the parent material to the unaltered rock. It is obvious, then, that the soil has been formed by the characteristic soil-forming processes, to be considered later, superimposed on the processes of rock weathering. We are here dealing with a soil formed *in situ*, or, as it is sometimes called, a *sedentary soil*. Fig. 1 shows a photograph of such a case of weathering of rock into a sedentary soil, as seen in a section of the Hythe Beds, near Great Chart, Kent.

When we examine the section of the gravel pit or the brick-earth working lower down in the valley, the sequence is not the same ; we still have the soil proper passing into the subsoil, and the raw material below, but below 3 feet or so, instead of showing a progressive change as we descend, it remains fairly uniform ; if it be gravel, the stones continue of the same size ; if brick-earth, neither stones nor stratified clay make their appearance. Should the exposed section be deep enough, we should find the raw material suddenly giving place to entirely different material—solid chalk, or massive clay, or sandstone, as the case may be—perhaps incapable, when disintegrated of furnishing the stuff of which the gravel or brick-earth is composed. In this upper stratum we see the clearest evidence of the action of water ; the brick-earth is free from stones and is of even texture, the gravel contains hardly any fine material and its constituent stones are worn and partly rounded ; only water can thus sift the heterogeneous results of the weathering of rocks and sort them into different grades. From what has been seen of the present work of the river, it is clear that the brick-earth was deposited where the water was moving slowly, in quiet bays and cut-offs, which only from time to time got filled with muddy water ; the gravel must have been laid down in the strongest wash of the currents.

Soils and subsoils (of this type,) which bear no necessary relationship to the underlying rocks, but whose parent materials have been carried from a distance by running water, moving ice, or wind are known as *transported* soils. The photograph, Fig. 2, shows the section of a deposit of glacial drift on magnesian limestone, in which the abrupt change from the stratified rock to the ice-borne boulder clay giving rise to the soil is very marked.

In making the distinction between sedentary and transported soils, it should be clearly understood that reference is intended to the parent material and not to the soil itself. Soil formation takes place *in situ* in both classes of soils, but whereas in sedentary soils the formation of the parent material takes place coincidently in space and more or less coincidently in time, in transported soils the two processes are separated both in space and time. Thus, the boulder clay that forms the parent material of a boulder clay soil was formed ages ago by the action of glaciers on rocks, often many miles away

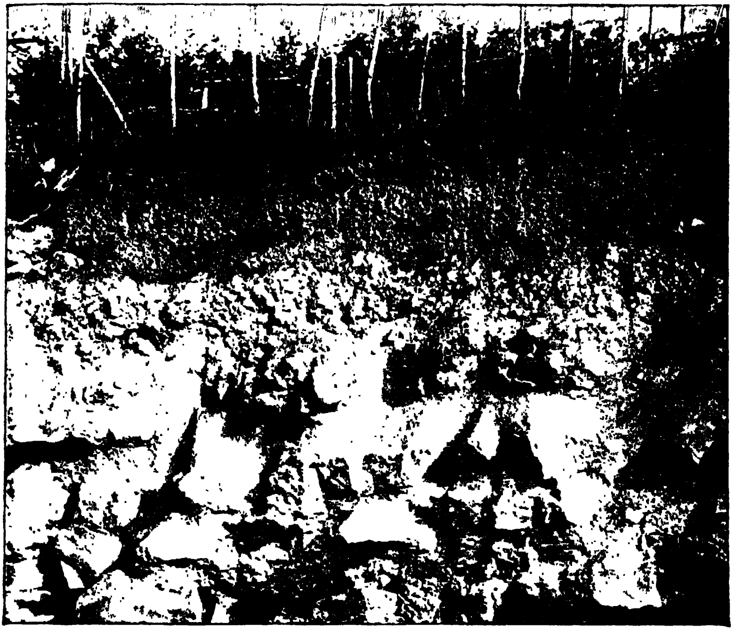

FIG. 1.—Photograph showing transition from Rock into Subsoil and Soil by Weathering (Hythe Beds, Great Chart, Kent).

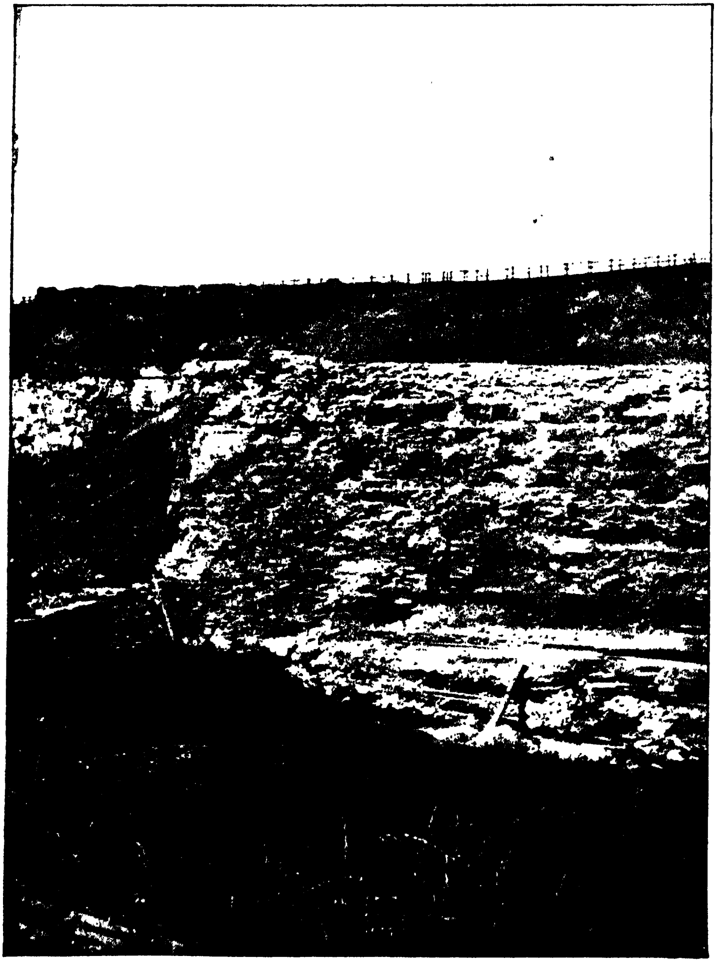

FIG. 2.—Photograph showing Glacial Drift overlying Magnesian Limestone

from the place of its present occurrence. The soil is formed from the boulder clay by contemporary processes.

The distinction between soil formation and rock weathering is shown diagrammatically in Fig. 3. Section A represents a succession commonly found in the tropics. The horizons of the soil profile occupy the top few feet, below which is a great depth of approximately uniform material, passing gradually at depth to the unaltered parent rock. In such a case the three stages, rock—weathered rock—soil are clearly distinguishable. In Britain, the distinction is not so clearly seen. This is shown in Section B, a common type of succession in British sedentary soils, particularly on the hard rocks of the north and west. Here, owing to the slower rate of weathering and the comparatively short time that it has been operative—since the close of the last Glacial Period—the depth of weathered material is much less and the soil profile invades the actual zone of rock weathering. Such soils are, of course, very immature and are sometimes called *lithosols*. Nevertheless, they can still show the essential features of a developed profile. In speaking of a soil as immature, therefore, it is necessary to consider whether the immaturity is not due to the low degree of weathering of the parent material rather than to the lack of soil profile development. Finally, in Section C is shown the kind of succession met with in transported soils. Here the soil profile is underlain by a depth of weathered material. It resembles the case of the tropical soil in Section A ; but it differs in that this weathered material has been formed elsewhere and bears no necessary relationship to the rock over which it is found.

Having made it clear that in speaking of transported soils we do not mean that the soils themselves have been transported as soils, but that it is the parent material that has been transported, we may divide these soils into (1) *colluvial soils*, in which the parent material is hill wash, transported downhill by gravity and occurring at the foot of slopes ; (2) *alluvial soils*, in which the parent material has been transported by water, in which class we may distinguish *river alluvium* and *estuarine alluvium* ; (3) *glacial soils*, derived from

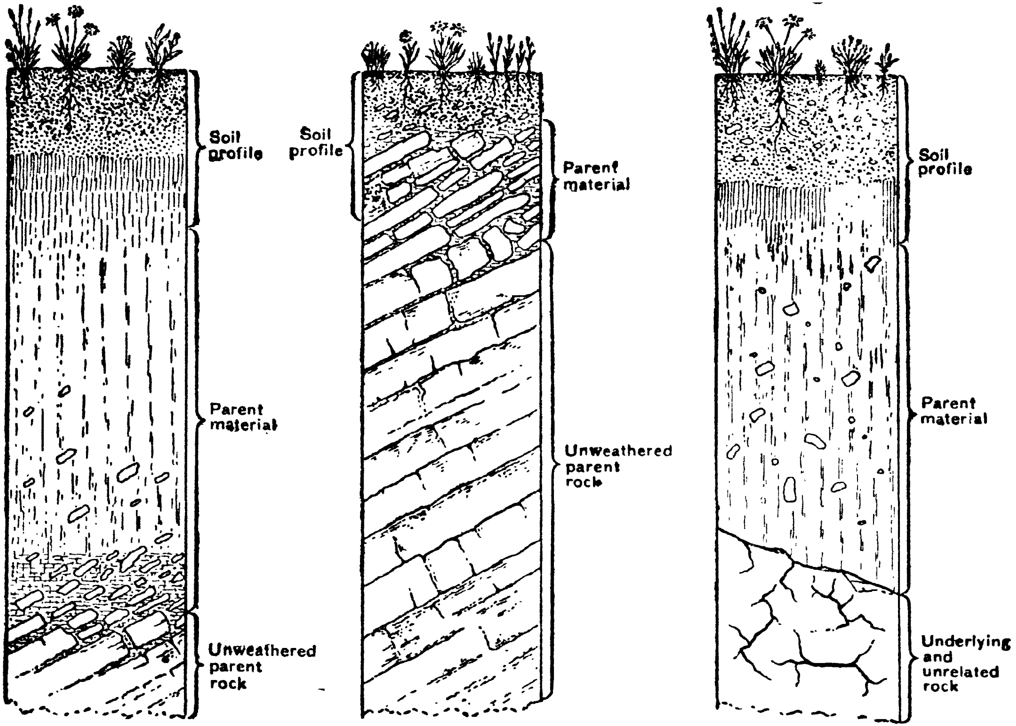

FIG. 3.—Soil Profile, Weathered Material, and Rock.

boulder clay or from glacial sands and gravels ; and (4) *aeolian soils*, derived from wind-borne material, such as sand-dunes, and the fine-grained deposits known as *loess*, which extend across Eastern Europe and Central Asia.

Rock-forming Minerals

The study of geology teaches us that, with certain exceptions,[1] all the rocks termed stratified or sedimentary that cover the greater part of the surface of the British Isles, have been formed from the waste of older rocks by weathering, and by subsequent transport and consolidation of the weathered material. A grain of sand, for example, is practically indestructible ; it may have become cemented to other grains on the sea beach where it was lying, and give rise to the rock that we term sandstone ; the rock thus formed may have been elevated into dry land, broken up into loose grains, and washed down to the sea to form a new beach, over and over again in the world's history ; so long a time has elapsed since water began to work on the earliest rocks. For this reason, if we want to trace out the origin of a soil in detail, we must go beyond the sediment or sedimentary rock from which it is immediately derived back to the so-called primitive or crystalline rocks, which represent in a sense the original materials of the earth's crust.

In the crystalline rocks we shall find certain fundamental minerals, which in a weathered state, altered both mechanically and chemically, go to form the sedimentary rocks and the soils that are our immediate study. In certain soils, termed soils of primary weathering, the parent material of the soil may be derived directly in place from an underlying crystalline rock. Such soils are common in other lands, notably in Central Africa. They are less common in our own country, but are found in parts of the north and west. They are generally shallow soils of comparatively low fertility.

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[1] Limestones, e.g. the Chalk and the Carboniferous limestones, have been formed from the calcareous debris of marine organisms and do not necessarily contain material from the weathering of rocks.

Although the number of distinct minerals known is very large, practically the mass of the earth's crust is made up of a comparatively small number of mineral types. They are essentially complex silicates of aluminium, iron, calcium, magnesium, potassium, and sodium, to mention the principal elements present. In the solid crust of the earth it has been calculated by F. W. Clarke that the chief minerals are present in the following proportions : felspars 57·8 per cent. ; quartz 12·7 per cent. ; micas 3·6 per cent. ; ferromagnesian minerals (hornblende, olivine, etc.) 16·0 per cent. It should be added that this is merely an estimate, and other estimates may vary somewhat from these figures.

The following table shows the composition of the chief minerals present in crystalline rocks :

	Silica.	Potash.	Soda.	Magnesia.	Lime.	Alumina.	Ferrous Oxide.	Ferric Oxide.	Water.
Quartz	100	...	...	...	...	...	...	...	...
Felspar Orthoclase	64·2	17	...	...	...	18·4	...	...	...
Felspar Albite	68·6	...	11·8	...	...	19·6	...	...	...
Felspar Anorthite	43·1	...	...	...	20	36·9	...	...	...
Mica	45 to 50	6 to 10	0 to 1·5	...	...	26 to 36	...	...	1 to 4·7
Hornblende Augite	39 to 49	...	...	10 to 27	10 to 15	3 to 15	3 to 20	...	...
Olivine	41	...	...	49·2	...	...	9·8	...	...
Talc	63·5	...	...	31·7	...	...	...	...	4·8

Quartz, the crystalline form of silica, is found massive and in veins, and in fragments of all sizes in granites, gneisses, and similar rocks. From the waste of these crystalline rocks are derived the sandstones of all geological ages, and, directly or indirectly, the sands now existing. In a sandstone rock the grains of quartz are bound together by a cement, which may be oxide or carbonate of iron, as in the Lower Greensand of Surrey and Bedfordshire, and in some of the Wealden sandstones, or calcium carbonate, as in the Kentish Rag, or even silica itself, as in the hard blocks of Tertiary sandstone, which are left as " grey wethers " on the surface of the chalk. In some of the older sandstones the rock is practically homogeneous, heat, pressure, and solution having thoroughly felted the grains together. Many sandstones weather rapidly, through the solution and removal of the cementing material ; the resultant sand has the same texture as it possessed before it was cemented together into a rock.

The degree of smoothness of sand grains gives some indication of the amount of wear and tear they have suffered since their origin as fragments of quartz from a crystalline rock. Below a certain size, however, quartz grains seem no longer capable of rubbing against each other, but remain angular even after long travel in running water. Any rounding of sand grains below about 0·1 mm. diameter is considered by Daubrée to be due to solution.

Silica in the crystalline state is very slightly soluble in water, a certain amount of solution taking place even at ordinary temperatures ; most natural waters show a little silica in solution, though this more probably arises from the hydrolytic decomposition of natural silicates during chemical weathering, rather than from actual solution from quartz.

Amorphous silica in the form of " flint " plays a conspicuous part in the constitution of many soils in the south and east of England ; owing to their durability and the former greater extension of the Chalk, flints are found in many districts remote from the Chalk, even in the drift beds of the Channel Islands. When freshly won from chalk, flints have a clear black translucent structure, and are easily fractured and crushed. When weathered, they become yellow or brown in colour, more opaque, and much harder. The surface also becomes covered with a white incrustation about $\frac{1}{16}''$ thick due to incipient weathering by frost action.

The Felspars.—These minerals constitute the most important group of minerals found in the crystalline rocks. The principal members are :

	Orthoclase or potash felspar	$K_2O.\ Al_2O_3.\ 6SiO_2$
	Albite or soda felspar	$Na_2O.\ Al_2O_3.\ 6SiO_2$
and	Anorthite or lime felspar	$CaO.\ Al_2O_3.\ 2SiO_2$

The felspars actually found in rocks generally represent intermediate stages between these theoretical compositions. In granite and other acid igneous rocks the common felspar is orthoclase ; in intermediate rocks, potash-soda felspars and soda-lime felspars are found ; whilst anorthite is found only in basic and ultrabasic rocks.

The felspars are all distinguished by the relative ease with which they are attacked by water containing carbonic acid, those containing lime more readily than those containing soda and lime. Owing to the disintegration of felspar in weathering, crystalline rocks containing felspars weather rapidly, the other materials, quartz, mica, hornblende, become loosened from the matrix and the whole rock becomes rotten. The granite of Cornwall and Devon is generally covered to a considerable depth, as much as 100 feet in some cases, with a layer of china clay or kaolin, in which the quartz and mica are embedded. The china clay of commerce is freed from these minerals by washing. From the decomposition of the felspars and other silicate minerals all our clays are formed ; as these minerals generally contain potash, they are the main source of the potash required by crops.

The Micas.—These are essentially double silicates of potash and alumina with some ferrous iron. There are two varieties of mica, namely, muscovite or white mica and biotite or black mica, in which the potash is partly replaced by magnesia. Mica splits up into minute flakes as the rock weathers, but the flakes are fairly resistant to chemical change and may be detected in most sands and sandstones. A modified mica known as hydrous mica or illite is sometimes found as a constituent of clays.

Ferromagnesian Minerals.—These are double silicates of ferrous iron and magnesium. They are more abundant in basic than in acid rocks. The commonest ferromagnesian minerals are olivine, hornblende, and augite. They undergo decomposition by the action of water containing carbonic acid, yielding ferruginous clays.

Calcium carbonate, though present in many crystalline rocks in the crystalline form as calcite or Iceland spar, generally occurs as a secondary mineral deposited from infiltrating waters. Calcium carbonate is soluble in water containing carbon dioxide in solution; hence when complex silicates containing lime are weathered, lime is removed in the form of calcium hydrogen-carbonate. Calcium carbonate is deposited from solution when the carbon dioxide escapes. In the massive form, calcium carbonate forms many of the sedimentary formations—the older ones hardened into limestones and the more recent ones soft like the chalk. In these rocks the calcium carbonate represents the calcareous skeletal parts of marine or fresh-water organisms. The crystalline structure, if present, is the result of later changes (metamorphism).

In the limestone and chalk rocks the calcium carbonate is never quite pure; in the white chalk the proportion is about 98 per cent. Certain crystalline limestones of the Carboniferous may exceed 99 per cent. calcium carbonate. In others there is a varying proportion of clay or sand, and all gradations may be found down to slightly calcareous marls and sandstones containing only a few per cent. of calcium carbonate. Occasionally the calcium is partly replaced by magnesium, giving magnesium limestone or dolomite. Pure dolomite has the theoretical composition $CaCO_3 . MgCO_3$.

Owing to its relatively high solubility, particularly in percolating waters containing carbon dioxide in solution, the weathering of limestone takes the form of removal of calcium carbonate more or less completely, leaving a fine-grained residue of clay or sand. Whenever a section is exposed in chalk or limestone, it will be noticed that the dividing line between weathered residue and rock is very irregular, often descending into pipes or cavities filled with residual material.

Apatite.—This is a crystalline calcium phosphate containing fluorine, to which the formula $Ca_{10}(PO_4)_6X_2$ (where $X_2 = F_2$, Cl_2, $(OH)_2$, or CO_3), may be assigned. It is present in small quantities in many igneous rocks, and is probably the ultimate source of the phosphorus compounds of soils.

Glauconite.—This is a hydrated silicate of iron, aluminium, and potassium, with a little calcium and magnesium, which occurs in dark-green grains in many sedimentary rocks, especially those of the Cretaceous system. It is to the presence of this mineral that the Greensand formations owe their name. It is also found in some Tertiary sandstones. It weathers, yielding hydrated oxides of iron.

Iron Pyrites, FeS_2, occurs in small brass-yellow cubical crystals in many of the older rocks, especially those of a clay character ; in another form, in fibrous masses of a lighter colour, it is called marcasite, and is common in the more modern clays, especially the London Clay, and again in round balls in the Chalk. Pyrites and marcasite readily oxidize to hydrated ferric oxide and sulphuric acid. Selenite or gypsum may be formed by the reaction of the sulphuric acid thus formed with calcium carbonate. In a finely divided condition iron sulphides form the colouring matter of many dark green or olive green rocks and clays.

Weathering of Rocks

The various agencies acting on rocks and reducing them to the weathered material from which soils are formed may be grouped into (1) mechanical weathering ; (2) chemical weathering ; and (3) biological weathering. In effect, however, the weathering of rocks by the agency of living organisms takes place either through mechanical or chemical processes.

Mechanical Weathering

In mechanical weathering, the only change consists in the comminution of the rock without any accompanying chemical change. Granite that has undergone mechanical weathering is still granite, or the fragmented minerals of which it is composed. Any further change can only occur through chemical weathering. We may consider briefly the principal agencies by which rocks are mechanically weathered.

In dry climates, the alternations of temperature between day and night set up sufficient strain to fracture even large rocks, and eventually reduce them to dust. The dust and sand of the deserts of Central Asia, the barren lands of the United States, and of many parts of both North and South Africa, are formed in this way; because of the dryness of the atmosphere, radiation is extreme, and the temperature of rock surfaces will rise to 60° C. in the day and fall rapidly to zero or lower immediately after nightfall. Crystalline rocks soon disintegrate under such alternations of temperature and the fine angular dust is transported by wind to the plains and valleys, giving rise to soils that are largely windborne. It has been supposed that the enormous *loess* deposits of Central Asia have originated in this way from the Asian deserts.

The most important mechanical weathering agency in temperate climates is undoubtedly frost acting upon water contained within the rocks and stones; the water expands as it changes into ice, and exerts an enormous pressure—indeed about 100 atmospheres would be required to keep water in a liquid condition at − 1° C. All rocks when freshly exposed hold, by capillary attraction, a certain amount of water known as the "quarry water," which amounts in the white chalk to as much as 19 per cent. A piece of such chalk will be shattered into fragments by a single night's frost. Even after the quarry water has been dried out the most close-grained rocks will absorb a small quantity of water. The face of polished granite rapidly deteriorates in severe climates, owing to the freezing of the water that finds its way into the minute divisions between the crystals: Cleopatra's Needle, which had retained its smooth face for centuries in Egypt, soon became affected after its removal to London, and has to be protected by a waterproof varnish, as have all the granite monuments in Canada.

In nature also, all rocks are traversed by joints and bedding planes; these cracks are filled with water and opened and extended by its conversion into ice in the winter, till finally a block is wedged off and a fresh surface exposed to the action. Where flagstones are quarried, the workmen are in the habit of saturating the surface of the rock with water before the winter sets in : thus the rock is split along its bedding planes more effectively than by any artificial means. The fragments that have been broken off the main rock will be continually reduced in size by successive frosts, until they reach the ultimate fragments, which are no longer penetrated by water ; even in a soil the disintegration is still proceeding.

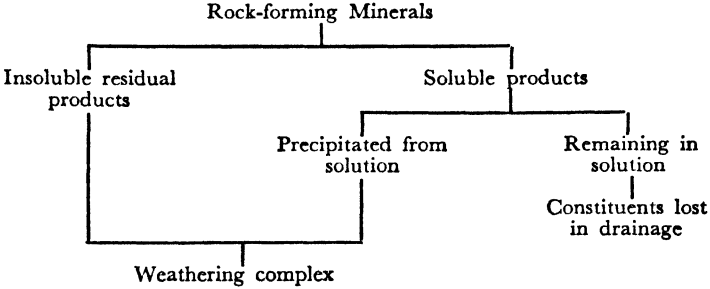
Although not operative in Britain at the present day, the action of glaciers has played a large part in the mechanical breaking down of rocks to form the glacial drift from which the soils of so much of our area are derived. For a full account of the work of glaciers, the student should consult a textbook of geology. For our purpose it is sufficient to note that during the Glacial Period (or, more correctly, Periods), most of Britain was covered by ice-sheets which swept away all former superficial deposits and wore down the rocks over which they travelled to form morainic material which survives to-day as boulder clay or, where re-sorted by post-glacial streams, sands and gravels.

In Scotland, the north of England, and Wales, glacial drifts are full of ice-scratched stones, and clearly represent material that has been ground down by a moving glacier ; but the origin of the glacial drift of the eastern counties is more obscure, for water seems to have played some part in its formation. These glacial drifts are often described as " boulder clays," but they are not necessarily very heavy or clayey in character from an agricultural point of view. Indeed, in Norfolk, as over a great part of Northern Europe, they may be of the lightest sandy type, and again in Cheshire, Staffordshire, etc., where, over large areas they are derived from Triassic sandstones, they do not differ greatly from light sedentary soils originating directly from these formations. When the glacial drift is derived from crystalline or hard sedimentary rocks, the resultant soils are marked by the predominance of angular fragments, " rock dust," that have undergone but little decomposition compared with the similar fragments in soils derived from soft sedimentary rocks.

Other agencies of mechanical weathering are running water and wind. In each case the effect is produced by the abrasive action of material in motion, the gravel and sand carried by rivers in flood and the blast of sand grains carried by the wind. From this standpoint these agencies are of comparatively little importance. The same may be said of the action of waves in breaking down the rocks of the coast-line.

Chemical Weathering

Chemical weathering differs from mechanical weathering in that minerals in the original rock are decomposed and new substances are formed. This type of weathering demands the presence of water because the first change consists in solution and it is in solution that the changes take place, whereby new substances are formed from the products of decomposition. The processes of chemical weathering may be represented diagrammatically as follows :


Rock-forming Minerals
Insoluble residual products
Soluble products
Precipitated from solution
Remaining in solution
Constituents lost in drainage
Weathering complex

The resultant secondary material or weathering complex is thus partly residual in origin and partly precipitated from the soluble products of weathering.

Not all the constituents of rocks are subject to chemical weathering, the principal unweatherable minerals being quartz and the iron oxides, such as magnetite. In a completely weathered rock the product will consist of the weathering complex together with the unweatherable minerals, principally quartz. Generally, however, chemical weathering is incomplete, and the weathered rock material contains a certain proportion of unweathered, but weatherable, minerals such as felspars and ferromagnesian minerals. Chemical weathering is most complete in the tropics and in materials that have undergone several weathering cycles such as the unconsolidated rocks of the more recent geological formations.

A number of different types of chemical weathering may be distinguished.

(1) *Simple Solution.*—Although most of the materials of which rocks are composed are practically insoluble in pure water, few of them, except quartz, can resist the attack of water containing carbon dioxide in solution. The rain-water when it reaches the ground has little carbon dioxide in solution, but the gases in the soil contain a considerable quantity derived from the decay of vegetable matter and the respiration of plant roots, and the water in contact with these gases will dissolve a proportionate amount. The proportion of carbon dioxide in the soil air varies with the aeration of the soil, the amount of organic matter present, and the season of the year, but at a depth of 1·5 metres, Wollny found it to vary from 3·84 to 14·6 per cent. at various periods of the year. Nearer the surface the proportion is smaller, but many times that in atmospheric air. From 0·3 to 1·0 per cent. are common figures. The water percolating down through the soil thus becomes a weak solution of carbon dioxide and attains a considerable solvent power. Probably some of the organic acids produced by the decomposition of vegetable matter aid in the solvent action of the soil waters.

As a direct weathering agency, the solution of calcium carbonate by percolating waters is first in importance. By comparison with other minerals calcium carbonate has a very high solubility, and rocks containing this constituent are rapidly disintegrated by its solution and the non-carbonate material is left behind as a residual product.

(2) *Oxidation.*—For our purpose, the only oxidation that

calls for consideration is the oxidation of ferrous iron. Ferrous iron is a constituent of many minerals such as olivine, hornblende, and augite. The products of the oxidation of ferrous silicates such as these are hydrated ferric oxide and silicic acid. Iron pyrites, FeS_2, a constituent of many sedimentary rocks, yields hydrated ferric oxide and sulphuric acid on oxidation. If calcium carbonate is present, the sulphuric acid may react with it to give gypsum, as may be seen in the upper layers of certain pyritiferous clays such as the Kimmeridge Clay. The hydrated iron oxides, produced by oxidation, give the reddish and yellowish colours to weathered material. The principal forms are limonite, goethite, and the anhydrous hæmatite. The actual colour varies with the degree of hydration and the state of division.

Hydration.—This type of weathering plays a subsidiary part and only affects certain minerals. The classic example is the change of olivine into serpentine by combination with water.

Hydrolysis.—This is by far the most important process in the chemical weathering of silicate minerals. It consists essentially in the liberation of silicic acid and the bases combined with it in the minerals undergoing decomposition. The alkaline and alkaline earth bases (Na_2O, K_2O, CaO, and MgO), liberated as hydroxides, go into the drainage as bicarbonates, sulphates, etc. The alumina and ferric oxides recombine with part or whole of the liberated silicic acid to form secondary complexes, which may be the forerunners of the characteristic clay minerals. Considerable differences of opinion exist as to the actual mechanism of silicate hydrolysis, but the general results are beyond dispute. They are as follows:

(1) Loss of silicic acid occurs. In humid climates this is removed by drainage and finds its way into rivers and ultimately to the sea. The silicic acid thus brought down by rivers is precipitated together with suspended matter in estuarine and shore sediments. In arid climates silicic acid liberated by hydrolysis is not removed but remains at the seat of weathering, giving a siliceous type of weathering com-

plex. In humid tropical climates the removal of silicic acid goes further than in temperate climates, and in extreme cases a residual complex consisting almost entirely of hydrated ferric oxide and alumina together with any unweatherable minerals such as quartz remains.

(2) Loss of alkaline and alkaline earth bases. These are removed under humid conditions mainly as sulphates and bicarbonates in the drainage. The resulting weathered product is therefore impoverished relatively to the fresh material in potassium, sodium, magnesium, and calcium. The case is different in arid climates, where the liberated alkaline and alkaline earth bases tend to accumulate as carbonates, notably calcium carbonate, in the weathered product.

The following analyses of Ebelmar show the chemical changes during the weathering of a basalt (Bohemia) and a dolerite (Cornwall), respectively :

	Basalt.		Greenstone.	
	Unaltered.	Weathered.	Unaltered.	Weathered.
SiO_2	44·4	42·5	51·4	44·5
K_2O	4·8	2·0	1·6	1·2
Na_2O	2·7		3·9	1·7
CaO	11·3	2·5	5·7	1·4
MgO	9·1	3·3	2·8	2·7
Al_2O_3	12·2	17·9	15·8	22·1
FeO	12·1	...	12·9	...
Fe_2O_3	3·5	11·5	3·0	17·6
TiO_2	trace	1·2	0·7	1·0
H_2O	4·4	20·4	1·7	8·6

The loss amounts to about 44 per cent. in the case of basalt, and 34 per cent. in that of dolerite.

The losses of potassium, sodium, calcium, and, to a lesser degree, magnesium are clearly seen. There is also a loss of silica. On the other hand, the proportions of alumina and ferric oxide are higher in the weathered product, indicating little or no removal. It is evident, then, that the weathering process, so far as it affects the weatherable minerals, such as felspars and ferromagnesian minerals, has as its end-point a mixture of hydrated alumina and ferric oxide. Only under tropical conditions is this end-point approached.

(3) New materials are formed from the decomposition of the original minerals. It has already been suggested that the end-point of weathering is a mixture of hydrated sesquioxides. More usually the weathering products or weathering complex consists of a mixture of alumino-silicic and alumino-ferric complexes. Among these products of weathering may be identified certain platy crystalline minerals, commonly known as the clay minerals. They fall into three groups, namely, the *kaolinite* group, with the general formula $R_2O_3.2SiO_2.xH_2O$, where R represents aluminium or ferric iron; the *pyrophyllite-montmorillonite* group, in which the molecular ratio of silica to sesquioxides is 3 to 5; and the *hydrous mica* group, which resembles the mica of crystalline rocks. Generally speaking, minerals of the kaolinite group predominate in material directly weathered from crystalline rocks. The more siliceous montmorillonites predominate in estuarine sediments and in the products of weathering under arid conditions, or where the parent rock is markedly basic.

Biological Weathering

The attack of frost and water upon rocks is much assisted by the roots of plants and trees. If we examine a fresh section of the soil over a quarry or brick pit, the roots of ordinary field plants can be traced downwards for 4 feet or more, whilst the roots of a tree may be seen working far into tiny fissures of the almost unaltered rock. The roots follow the water in the fissures: at first they can enter very minute cracks; as they grow, the pressure they exert widens the cracks; finally the roots decay and leave a channel down which water can percolate freely. The fine roots themselves cause a certain solvent action; after plants had been grown in a pot filled with powdered granite rock, which had been freed from all fine particles by washing, an appreciable quantity of mud and clay was found to have been formed.

The opening up of the subsoil to weathering by the action of roots is also carried out by worms, which have been observed making their burrows to the depth of 5 feet, thus introducing both air and water into the lower strata. But the great work of worms in regard to soil lies rather in the production of the fine surface layer of mould rich in vegetable matter : Darwin calculated that on an ordinary chalky pasture the whole of the fine surface soil to a depth of 10 inches was passed through worms and cast up on the surface in the course of fifty years. During their passage through the gizzard of the worms the stony particles will receive a certain amount of rubbing and be reduced in size, so that some of the fine particles in the soil owe their origin to worms. The deposit of the fine soil on the surface in the shape of worm casts, which are afterwards spread by the action of rain and wind, explains why chalk, ashes, or even stones placed on pasture land gradually sink below the surface. Darwin found in one case that a layer of burnt marl spread on the surface had sunk 3 inches in fifteen years, in another case a layer of chalk was buried 7 inches after an interval of twenty-nine years ; in neither case, however, can we estimate the part played by the accretion of dust in forming this deposit. When we consider for how long a period worms must have been working in our cultivated soils, it is clear that the whole must have been through them over and over again, and that much of the fineness of the surface soil must be due to their action, both in actually grinding the fragments and in constantly bringing the finest portions back to the top.

Soil Formation

Hitherto we have been considering the processes of weathering, in other words the processes whereby the parent materials of soils are formed. We have now to consider the processes whereby this weathered material becomes soil. Before proceeding further, however, it should be noted that these two great sets of processes do not always take place successively. Where soil development takes place in material that has been weathered and transported to form a considerable deposit, we can indeed speak of soil formation as being consequent on weathering. Such is the case where soil is formed from alluvium, or from sedimentary rocks such as the Tertiary clays that have not undergone alteration. In shallow sedentary soils on hard rocks the processes of weathering and soil formation must be regarded as proceeding concomitantly.

We may regard the processes of soil formation, resulting in the development of the soil profile, as falling into two groups. The first group of processes result in the addition of organic matter to the soil in the form of humus. The second group of processes are concerned with the removal of soluble or mobile constituents from the surface layers and their removal in drainage or their deposition in sub-surface layers. The effect of these processes is to form the soil profile.

The soil profile, the succession of soil horizons down to the parent material, expresses the result of the soil-forming processes acting on the given parent material. There is also a time factor, for the process of profile development require hundreds or even thousands of years to complete their work. A profile that has attained its full development is called a *mature* profile. Such profiles occur in moderately level country long occupied by natural vegetation. It is easy to understand that mature soil profiles are not commonly found in Britain, because most of our area has been subjected to human interference, and those parts of the country under natural vegetation are often broken or mountainous. There is the further reason that soil development in Britain does not date back further than the close of the last glacial period. Profiles that are still in the process of development are termed *immature* profiles. The soils of river terraces, or sand-dunes, even if they are under natural vegetation, are still only in the early stages of development. Where the natural vegetation has been broken up and the soil brought into agricultural use by cultivation, the soil horizons down to the depth affected by tillage become mixed together, and the result is a *disturbed* profile. Where erosion is active the surface soil may be removed and a *truncated* profile is obtained. Many soils of steep slopes are modified in this way, because the removal of the surface layers by downwash may proceed as rapidly as the development of the soil horizons.

Development of the Organic Matter Profile.—The organic matter of soils originates from the residues of the vegetation growing on them. Under agricultural conditions there are also additions of organic matter in the form of farmyard manure, containing the excreta of animals that have fed on the products of the soil. Considering soils under natural vegetation, we may distinguish between forest and grassland, including prairie or steppe, as contributing to the soil organic matter. Under forest the main contribution to the stock of soil organic matter is through the leaf-fall or litter. This, being at the surface, is exposed to considerable loss by biological oxidation and much of it never becomes part of the soil. In grassland, on the other hand, the main contribution is from the decay of surface roots and thus a more considerable proportion of each year's growth becomes incorporated with the soil. Accordingly we find that, under similar climatic conditions, grassland or prairie soils are much richer in organic matter than forest soils, particularly if the forest forms a close canopy, restricting the development of a ground vegetation.

In the assimilation of the residues of plants to the soil, an important part is played by earthworms and, in tropical countries, by termites or white ants. Whilst there is little evidence that earthworms have any chemical effect on plant residues, they do undoubtedly prepare the way for biological and chemical decompositions by breaking down the leaves and stems of plant material and carrying it into the soil. Their effect is thus to comminute the plant residues and to mix them with the soil down to a depth of 2 or even 3 feet. Where, owing to extreme acidity, earthworms are absent, the residues of vegetation tend to accumulate as a layer of raw humus at the surface.

The base-status of the soil has an important effect on the course of decomposition of plant residues by micro-organisms. These decompositions will be considered in more detail in a later chapter. Under neutral or alkaline conditions plant residues undergo a decomposition, whereby they are partly oxidized to carbon dioxide and water and partly changed to form the so-called mild humus characteristic of fertile agricultural and forest soils. Under acid conditions, residues are changed into an acid type of humus, known as raw humus, which may be seen in the peaty surface layer of heather moors.

The air conditions in the soil also influence the course of organic matter decomposition. With excessive aeration, as in open gravelly or sandy soils, residues are rapidly oxidized and little accumulates in the soil in the form of humus. High temperatures have a similar effect. On the other hand, with defective aeration, as in water-logged soils, plant residues undergo anaerobic decomposition to form peat.

The organic matter status of the soil and its distribution in the soil profile is thus governed by the rate at which plant residues are added to the soil and by the balance between oxidative decomposition and humus accumulation.

The addition of organic matter to the weathered material changes it from an inert mass to a living soil. In the first place the addition of organic matter to the soil leads to the aggregation of the mineral particles into compound particles or crumbs. The soil thus acquires a porous structure, which makes possible the movements in it of water and air. This effect may be easily appreciated by comparing the surface of a tilled field with that of land from which the surface soil has been removed for building or construction works. The agricultural soil freely absorbs the heaviest rain, whilst the raw clay or sand soon becomes water-logged, with pools of water standing on its surface.

Of equal importance with the effect of organic matter of the soil on its structure is the development in the soil of a micro-flora and micro-fauna. The decompositions of organic matter in the soil are almost entirely the work of micro-organisms, principally bacterial and fungi. These decompositions are important for the maintenance of the characteristic soil structure ; they are also of the highest significance in rendering available for the use of plants the reserves of plant food in the soil organic matter. Indirectly they also play a part in the weathering of the mineral reserves of the soil.

Eluviation.—The other great group of processes of soil formation are commonly included in the general term *eluviation.* By this is understood the removal of material in solution, colloidal solution, or even in suspension, in a vertical direction from one horizon to another by water movements. Generally speaking, these movements are in a downward direction, but in certain circumstances, the drying out of the surface soil may result in ascending movements.

The character of the eluviation processes in a soil will depend on climate, but will also be affected by the regional drainage conditions. In a freely drained soil in a climate such as our own, where rainfall predominates over evaporation, there is a general movement of moisture down from the surface to the level of the ground-water. The soil profile is leached in the same way that a precipitate is washed on a filter.

The case is different in arid and semi-arid climates. Here, intermittent rain moistens the soil down to a limited depth and the ensuing drought dries it out again. Below the depth to which the rainfall penetrates, there is a zone extending down to the regional ground-water level that is practically unaffected by ordinary rainfall. This type of moisture régime obtains even in a generally humid climate during periods of prolonged drought.

Finally, there is the possibility that the downward percolation of rain falling on the soil may be impeded by a high water-table or the occurrence of strata impervious to water movements. In such cases the excess of water reaching the soil by rain can only escape laterally.

Water movements in the soil are accompanied by translocation of material. In the main, as has been already stated, this movement is in a downward direction. The effect of this eluviation is to remove certain constituents from the surface horizons. Material thus removed or eluviated is either deposited in lower horizons or else removed altogether in drainage. It is customary to refer to the upper horizon from which material has been eluviated as the eluvial or A-horizon. The horizon or horizons in which material is deposited is termed the illuvial or B-horizon. Below it, in normally drained profiles is the parent material or C-horizon. The A- and B-horizons are sometimes referred to together as the *solum*.

Two types of eluviation may be distinguished, namely, *mechanical eluviation* and *chemical eluviation.* Mechanical eluviation consists in the downward washing of fine material, principally clay. This leads in extreme cases to the development of a well-marked texture profile in which the A-horizon consists of sandy material and the B-horizon of a compact layer formed by the deposition of fine material. Such profiles are not strongly developed in this country, where the soils are generally disturbed or immature, but it is quite usual to find that subsoils are heavier in texture than their topsoils.

In chemical eluviation, there is a partial decomposition of the colloidal complex of the soil. Certain constituents are carried down in the profile whilst others remain in the A-horizon. The type example of this kind of eluviation is furnished by the so-called *podsol* profile developed in cool humid climates under forest or heath vegetation on parent materials of low base-status. Under such conditions a layer of raw humus is developed at the surface. Water percolating through this layer becomes charged with organic acids from the acid humus. In the presence of such solutions the colloidal complex splits off free silicic acid and sesquioxides. The sesquioxides go into colloidal solution, in association with humic matter and sink in the profile. At lower levels precipitation takes place, first the humic matter and immediately below it the sesquioxides. The mature profile is thus characterized by the following succession of horizons :

A_0 Raw humus layer.
A_1 Mineral soil with dark-coloured humus.
A_2 Mineral soil, bleached by removal of sesquioxides.
B_1 Dark-coloured horizon with humus deposition.

B_2 Yellow, orange, or rust-coloured horizon in which ferric oxide and alumina are precipitated.

C Parent material from which the soil has been developed.

This type of profile is illustrated in the Frontispiece. (Cf. p. 266.)

There are naturally many variants of this profile. The B_1-horizon may be missing, and more than one horizon of sesquioxide deposition may be seen.

In immature profiles the bleaching in the A_2-horizon may be scarcely perceptible, or it may be masked by the presence of humic material. Where eluviation is less intense, or where the parent material has a better base-status, sesquioxides may remain in the A-horizon and the whole profile has a brown or yellowish-brown colour.

In soil profiles developed under humid conditions soluble salts and calcium carbonate are completely removed from the soil profile. Under drier conditions, the removal of salts may occur, but the eluviation may not be sufficient to remove calcium carbonate from the profile, and a layer of calcium carbonate deposition may be found in the subsoil. The base-status of the soil is fairly high and there is no decomposition of the colloidal complex. The soil colours are generally greyish, and, as such soils are associated with a steppe or short grassland vegetation, there is a high organic matter status and the soil has a dark colour. The classical example of this type of soil is the tshernosem or black earth of South Russia.

Impeded drainage conditions result in anaerobic conditions in the soil profile. Where these conditions persist, reduction processes result in greyish or bluish-grey colours owing to the presence of ferrous compounds. In the zone where conditions are alternately aerobic and anaerobic, hydrated ferric oxides are deposited in characteristic streaks or mottlings.

Human Interference as a Soil-forming Factor

Among the factors involved in the development of the soil profile, human interference must not be overlooked. In our own country most of the soils with which we have to deal have been profoundly modified from their original condition by human activity.) The period over which this interference has operated varies greatly. Some soils have been brought into cultivation in comparatively recent times, whilst other soils may have been in human occupation, or at least affected by human activities, for thousands of years. The areas of soil that can be definitely described as natural are comparatively limited and are confined to certain woodland areas, such as parts of the New Forest and the higher mountain areas. The fact that land is waste at the present day does not mean that it has not been modified by man. (Great areas of our rough grazings were formerly forest. Deforestation and the establishment of a grassland or heath vegetation, with the occupation of the land by grazing animals, have resulted in considerable changes in the type of soil profile.)

The most spectacular result of human interference on the soil profile is *erosion*. When primitive forest or prairie is cleared and put into arable cultivation, the first result is a lowering of the organic matter status and a deterioration in the stability of the soil structure. This may take place very rapidly in warm climates, and if the climate is characterized by periods of intense rain, as is the case in part of the eastern United States, the top soil may be removed by surface run-off. Erosion may take the form of a general removal of the surface soil or it may be localized in channels so that gullying takes place. In some of the high rainfall regions of the United States, gulleys 40 or 50 feet deep may be seen, extending for a mile or more. It is evident that this type of erosion is a serious menace to agriculture. Sheet erosion, whilst less striking, is equally serious, for it may mean the removal of large areas of relatively fertile top soil and the exposure at the surface of subsoil, poor in plant nutrients and lacking the porous open structure of the surface soil. A further disadvantage is that the material washed away by erosion may be deposited at lower levels either over the surface of existing soils or else along river channels, which are thereby silted up.

An equally serious kind of erosion is wind erosion. This occurs in drier climates, particularly where land has been exhaustively cropped, so that the organic matter status has been lowered to the danger point. Serious examples of this kind of erosion were seen in 1934 when, following a serious drought, dust-storms swept across the states of Texas, Oklahoma, Kansas, New Mexico and Colorado. Whole farms went up into the air, with disastrous results. It is probable that much of the land in this region—the Great Dust Bowl, as it has been called—should never have been brought into cultivation, but should have been left as range-land.

Serious erosion, with loss of valuable agricultural soil, occurs in many other countries, notably in the humid tropics. It has also occurred in past centuries in Mediterranean countries. In the British Empire and the United States, the seriousness of the problem of soil erosion has been realized and measures are being taken to check this destructive process. In the United States, a great organization, the Soil Conservation Service, undertakes measures against erosion, including the replanning of farms and whole sections of the country, the most famous example being the Tennessee Valley Authority, which has replanned the land use of an area larger than England with a view to diminishing erosion and controlling floods.

Erosion in our own country is not at present a serious menace to agriculture. It may be seen on a very limited scale on steep arable fields following heavy thunder rain, particularly on light soils, but the extent of such erosion is very limited, and must be regarded rather as exceptional than as a normal occurrence. Wind erosion may be seen in parts of the eastern counties on light sandy soils during droughts. The consequences are serious for individual farms, but the proportion of our total area menaced by erosion is very small.

There is some evidence that erosion may have been more serious in the past, following deforestation and pioneer cultivation. There are areas in North Wales where the surface soil has the characteristics of an illuvial horizon, whilst in depressions in the adjoining lowlands are soils having some of the characters of podsolic A-horizon material. It may be that the former soils are essentially truncated podsols, and that the truncation took place through catastrophic erosion following deforestation centuries ago. On the other hand, it may also be that these conditions have been brought about by normal erosion, which would always tend to remove the A-horizon as it develops.

The general effect of erosion is to produce truncated profiles. The removal may proceed to varying stages, in some cases even to the removal of the soil horizons and the exposure of the parent material. Where soils are in agricultural use, the exposed subsoil may be brought into use and function as an agricultural soil. Large areas in the United States are growing cotton on what were originally B- or even C-horizons. Similar cases probably occur on the heavy clays used for the growth of sugar-cane in Trinidad. Here, as in many other parts of the world, crops are grown on what is not, strictly speaking, developed soil at all, but parent material which has been made productive by human effort.

Whilst erosion on a catastrophic scale results in the partial or complete removal of the soil horizons, normal erosion is desirable. If no normal erosion took place, the weathering agencies described above would gradually cover the rocks of the earth's crust with a layer of débris, which would protect the lower layers from further action. The processes of profile development would then proceed to an end-point which would be a chemically and biologically inert soil. Such a condition could hardly occur in this country, but cases approximating to it may be found in the tropics in the lateritic soils. In perfectly flat areas, age-long eluviation may result in the development of heavy clay-pans, which restrict drainage and render the soil infertile

Apart from the effect of human interference in causing erosion, there are other consequences which may be observed and studied in our own country. Consider the case of a forest soil that has been cleared and brought into ordinary agriculture. The original profile, if the soil was a brown earth, probably consisted of a layer of leaf litter and mould, passing through a thin layer, in which there was a mixture of mineral soil and humus, to a granular or crumb horizon of moderate humus content, in turn succeeded by a lighter coloured horizon with a coarser structure. Under agricultural use the upper horizons have been mixed together and can no longer be distinguished. There has been a rise in the organic matter status of the profile as a whole, because in the virgin state, the high organic matter content was confined to the immediate surface. Of course, if there has been exhaustive cropping there may be a loss of organic matter, as has been the case with many pioneer agricultures. Good husbandry, particularly in a country such as our own with its temperate climate, should result in an increase of organic matter, since it involves the return to the soil of a considerable proportion of the crops grown in the form of farmyard manure and the residues of temporary or permanent leys. Where forest is replaced by grassland the rise in organic matter status is still more marked.

Agriculture should also involve a rise in the lime-status of the soil, for good husbandry implies the maintenance of a good lime-status. This in itself will tend to oppose podsolization. Indeed, there is some evidence that agricultural use may even reverse podsolization. There will also be a general rise in the plant nutrient status of the soil. Where the soil is in grassland the rise in the organic matter status is more marked than under arable cultivation. On the other hand, where the grassland is not well managed, and liming is neglected, as was the case until recently over a large proportion of our agricultural area, the base-status may fall and the tendency will be for the grassland to degenerate to heath, with accompanying podsolization. This may be seen in many grassland soils in the wetter districts of Wales and Scotland.

Changes may take place in the drainage conditions of soils as a result of utilization. There are large areas of originally wet land that have been improved by drainage. For a considerable time the characteristic marks of drainage impedance persist, but eventually, the profile changes its character and, with better aeration, assumes the properties of freely-drained soils.

Soil and Subsoil

Although the transition from soil to subsoil is gradual, the distinction between the two is, as a rule, easy to be made ; the change begins an inch or so below the usual limit of cultivation on arable soils, on pastures at the depth to which the mass of the roots penetrate. The most obvious difference between the two lies in the comparative richness of the staple in decaying vegetable matter or humus, which indeed would be entirely confined to the surface layers were it not for the decay of the deeper roots and the work of worms. To the humus is also due the difference in colour ; not only does the colour deepen towards black as the proportion of humus increases, but in some cases the sands and clay are to a greater or less extent bleached through the removal of the iron oxides which colour them ; hence the inorganic material is lighter and duller in colour in the soil than in the subsoil. In stiff clays the subsoil often shows signs of imperfect oxidation at comparatively slight depths. On an old pasture on the Gault Clay a trench was dug ; the top 3 inches were black or nearly so and gradually changed to a stiff brown loam which extended to a depth of 9 or 10 inches, becoming lighter and more distinctively yellow as the admixture of humus diminished ; below this depth the clay became mottled, grey and yellow mixed, till at a depth of 4 feet practically the whole was a dark blue unweathered clay, owing its colour to iron pyrites and glauconite or kindred silicates of ferrous iron. One of the greatest distinctions between soil and subsoil lies in their respective texture ; in humid climates like our own the soil is almost invariably composed of coarser grains than the subsoil, though in arid climates soil and subsoil appear to be almost uniform. This is due to the rain, which constantly percolates through even the stiffest soils and washes down the finest particles ; in heavy rains also, water runs off the surface into the ditches, carrying with it the finest particles of the soil and leaving behind the coarser grains on the surface. Naturally, this loss of the finer particles is greater as the soil is more worked and made open to percolation and washing; to some extent it is counterbalanced by the work of worms bringing the fine mould to the surface from below, so that the difference is least in an old pasture. It is greatest in an old garden soil, where the constant working and further opening of the soil by the introduction of bulky manure often results in so complete a washing down of all the finer particles that the soil proper loses its power of cohering, falls into dust when dry, and is popularly said to be "worn out."

In addition to its humus the soil is nearly always richer than the subsoil in all the essential elements of plant food, despite the fact that crops have been raised on it for generations; the crops, in fact, have been the cause of the difference, for the deeper roots draw food from the subsoil and leave it behind on the surface as the plants decay. Potash is perhaps an exception in this connexion, being essentially a product of the weathering of felspar and removable from the soil by water containing carbonic acid: it is often more abundant in the comparatively unweathered subsoil. The richness of the humus, its greater warmth, and the freer access of air also cause the soil to be more abundantly supplied with those organisms which play such an important part in preparing the food of the higher plants: as will be seen later, subsoils become almost without living organisms at a very slight depth.

For all these reasons—the absence of humus, and of the organisms associated with it, the comparative poverty in inorganic plant food, the presence sometimes of unoxidized material, and on stiff soils the great change of texture—the subsoil is often comparatively unfertile and may be almost barren. Desirable as it is to work the subsoil and open it to the access of air and the free penetration of roots, all methods of cultivation should be avoided that would bury the surface soil and bring the subsoil to the top. A plough which inverts the soil should not go far below the former limit of cultivation, and if it is desired to deepen this limit, it should be done by degrees, half an inch or so each year. Immense damage has been done to the fertility of many of the heavier soils by rash ploughing with steam, especially where the old " lands " were thrown down, burying the fertile soil in the furrows and baring the raw clay on the tops of the ridges.

CHAPTER III

PROXIMATE COMPOSITION OF SOIL

Mechanical Composition of Soils: Clay; Calcium Carbonate; Humus—Soil Solution—Soil Air.

WE have seen that soils are derived from the waste of rocks. They consist, therefore, of a mass of particles of varying sizes from gravel and sand down to the finest clay particles, together with a certain amount of humus of vegetable origin. They may be roughly classified according to the predominance of the different sized particles present. This is the practical classification of soils into sands, sandy loams, light loams, medium loams, heavy loams, and clays.

Mechanical Composition of Soils

Mechanical analysis consists in pushing this rough " eye and hand " classification a stage further and actually determining the relative proportions of the different sized particles present. Upon the physical make-up of the soil thus determined, or as we shall term it, the *texture*, depend some of its most important characters, particularly its behaviour with regard to the supply of water to crops and its amenability to cultivation.

A detailed description of methods of mechanical analysis lies outside the scope of the present work; but it will help the reader to understand the significance of the results obtained if the general principles of this analysis are briefly discussed. The discussion will also throw further light on the constitution of the soil.

As already stated, the object of mechanical analysis is to determine the relative proportions of the different-sized particles present in the soil. To do this it is first necessary to submit the soil to a pre-treatment in order to break down all compound aggregates or crumbs and bring the soil to a state in which all the particles are separated from each other. This state is sometimes referred to as the *prime particle structure.* Until this structure has been attained, it is impossible to determine the relative proportions of the ultimate particles present, because a cluster of small particles grouped together into a compound particle or crumb will behave in the same way as a larger particle.

The compound particles are held together by a kind of cement or binding material consisting of humus and the finest clay particles, or as it is sometimes termed, the soil colloid. This cement must be loosened before the constituent particles of the aggregates can be freed of each other. The first operation consists in boiling the soil with 6 per cent. hydrogen peroxide. This oxidizes the humus, and the oxidized soil can be seen to be lighter in colour than the original soil. A considerable breakdown of crumbs also occurs in the process. The breakdown is not complete, however, and to carry the dispersive process still further, the oxidized soil is treated with dilute (0·2 normal) hydrochloric acid. This dissolves out any calcium carbonate present and also brings into solution as chlorides any bases, of which the principal is generally calcium, combined with the soil colloid. After filtration and washing, the base-free soil is obtained. This is now suspended in a weak alkaline solution (0.008 normal sodium hydroxide) and shaken in a suitable bottle for about two hours. The particles of soil in the suspension are now all independent of each other and the prime particle structure has been attained.

It is now necessary to submit the dispersed soil to the actual mechanical analysis. The first question to decide is : what fraction grades shall we distinguish ? There were formerly a large number of different scales of fraction grades in different countries, but these have been replaced in most countries by the so-called International Scale, in which the particle-size limits are as follows :

	Diameters.
Coarse sand	2 mm. to 0·2 mm.
Fine sand	0·2 mm. to 0·02 mm.
Silt	0·02 mm. to 0·002 mm.
Clay	less than 0·002 mm.

These limits are, of course, conventional, as is also the convention that the analysis is made on material passing a 2-mm. sieve, thereby excluding from the analysis gravel and stones above 2 mm. in diameter. There is, however, some justification for taking 2 mm. as the upper limit, because particles above this size are mainly rock fragments, whilst particles below this size are mainly mineral particles. The limit of 0·002 mm. for the clay also marks approximately a change in the character of the material, for below this diameter the particles are mainly secondary products of chemical weathering, including the characteristic clay minerals. There is some overlap, however, for small fragments of unweathered minerals may occur in the upper part of the clay range, whilst secondary material may occur in the lower part of the range above 0·002 mm.

The coarsest fraction may be separated by sieving, using a 70 mesh I.M.M. sieve, giving an approximately 0·2 mm. aperture. Sieving is inapplicable for the separation of the finer particles and use is made of the principle of subsidence. Various methods are used, all depending on the well-known Stokes's law relating the velocity of fall of a particle through a liquid to its size and density and the viscosity of the liquid. When v is the velocity of fall of a particle of radius r and density σ in a liquid with density ρ and coefficient of viscosity η, then

$$v = \frac{2gr^2(\sigma - \rho)}{9\eta}.$$

This formula would in strictness only apply to spherical particles ; it is, however, used to gather into groups the particles having velocities between particular limits which behave as if they ranged in size between the defined limits.

The earliest methods of Schöene, Nöbel, and Hilgard depended upon the employment of a current of water of varying velocity, which at each velocity is able to carry with it the particles below a certain grade. Technical difficulties caused the general replacement of these processes by sedimentation methods based on the ability of particles below a certain grade to remain suspended in still water for a given time correlated with the height of the water column. If a soil is dispersed in water of a given depth for a determined time it is evident that whatever particles remain suspended at the end of that time are below the size grade which will fall through the specified distance in the time. The separation will not, however, be complete because the sediment includes such of the small particles as had to fall less than the specified distance, as well as a certain number dragged down with the larger ones. In consequence, after making a first separation by pouring off the liquid containing the small particles, the sediment must be made up afresh into a suspension, allowed to stand for the given time, and again separated by pouring off the liquid carrying the suspended particles. These will be of the same grade as before and may therefore be added to the previous decantation. The making up of the suspension and pouring off is repeated as often as necessary until the water above the sediment is clear after standing the specified time. Then the successive decantations will contain all the particles below the size grade correlated with the length of water column and the time of standing. The sediment can then be worked up afresh and divided by selecting either a shorter column or a shorter time of standing. A standardized method based upon this principle was employed in Great Britain until recently, the only objection to it being the time required (for the separation of the clay fraction twenty-four hours standing was required and nine or ten successive decantations might be necessary) and the volumes of liquid that had to be evaporated to obtain the suspended fractions.

The method now generally used in place of the decantation method depends upon drawing off with a pipette aliquot portions of a suspension in water. If we imagine a soil, made up of a number of sets of particles each of a defined size, to be shaken up with water and set to subside in a column, then after a given time there will be in the topmost layer only particles of the smallest size, A. But at a certain distance from the top, i.e. the distance through which they can fall in the time, the particles of the next larger size, B, will begin, and below this point there will exist a zone containing such particles together with A particles similar to those floating in the top layer. For the same reason somewhat lower will begin a zone into which the particles of the next larger size, C, have fallen, mixed as before with A and B particles. If now we can draw a sample from each of these zones and weigh the material therein, the uppermost will give the proportion of A, the next zone the proportion of A + B and the third the proportion of A + B + C.

In the standard method as used in most countries, the suspension obtained after dispersion is made up to a known volume, of concentration equivalent to 2 per cent. of the original soil taken, again shaken and allowed to stand for 4 minutes, 48 seconds at 20° C. Changes in the viscosity of water with temperature are allowed for by varying the sampling time accordingly. A 20 c.c. sample is then taken by means of a pipette lowered into the suspension until the tip is 10 cm. below the surface. The sample is taken to dryness at 105° C. and weighed. From the weight thus obtained the concentration at the point and time of sampling is calculated. This expressed as a percentage of the original concentration gives the percentage of silt and clay, i.e. the percentage of particles having a settling velocity less than 10 cm. in 4 minutes 48 seconds. For example, if the weight of dry matter in the 20 c.c. of suspension is 0·240 g., then the concentration of the suspension at that point and time is $5 \times 0{\cdot}240 = 1{\cdot}2$ per cent. If the suspension has been made up by starting with 10 g. of soil and making up finally to 500 c.c., the equivalent original concentration is 2 per cent. and the percentage of silt + clay is $1{\cdot}2/2{\cdot}0 \times 100 = 60$ per cent.

The suspension is then shaken up and allowed to stand for 8 hours, after which it is sampled in the same way at 10 cm.

depth. From the weight of dry material in the sample of suspension, the percentage of clay can be obtained. This, subtracted from the former figure, gives the percentage of silt.

By decantation of the remaining suspension, the silt and clay are separated from the sand fractions which are themselves separated by sieving.

The fractions in a mechanical analysis are calculated and shown as percentages of the total soil dry at 105° C. Since the humus has been mainly removed by the peroxide treatment and any carbonates present by the acid treatment, the percentages of the fractions add up to less than 100, the difference representing the carbonates and the humus removed in the pre-treatment. No significance can be attached to this figure, as it is loaded with the errors of all the determinations made. If calcium carbonate is present it is determined separately. The mechanical analysis is usually supplemented by a determination of the organic carbon content. This is done in order to obtain a measure of the amount of organic matter present. A conventional factor 1·724 is used to multiply the organic carbon to convert it to organic matter. This is admittedly unsatisfactory, but no satisfactory method is at present available for direct determination of organic matter. Loss on ignition is sometimes reported and used as a measure of organic matter. But, since the loss on ignition includes water chemically combined with clay and also carbon dioxide driven off from any calcium carbonate present, the figure is too high and therefore untrustworthy as a measure of organic matter.

It is convenient for purposes of comparison to re-calculate all the fractions in a mechanical analysis as percentages of the total fractions present. The following example will illustrate this. The actual percentages found are shown in the first column of figures, whilst in the second column of figures are given the percentages calculated to 100 per cent. :

	Actual.	*Calc. to 100 per cent.*
Coarse Sand	2·3	2·7
Fine Sand	12·6	14·5
Silt	44·8	51·8
Clay	26·9	31·0
Diff. from 100	13·4	0·0

In the following table some typical analyses calculated on this basis are given. The percentage of organic matter, obtained by multiplying the organic carbon figure by 1·724 and the loss on ignition, is also given in each case.

MECHANICAL ANALYSES OF TYPICAL SOILS.

	Heavy Clay. Trinidad.	Heavy Loam. Caernarvon.	Heavy Silt Loam. Denbigh.	Medium Loam. Monmouth.	Medium Loam. Herts.	Light Loam. Caernarvon.	Coarse Sand. Cheshire.
Coarse Sand .	2·4	8·3	1·5	9·3	33·3	21·0	52·0
Fine Sand .	2·6	17·8	10·0	43·9	29·2	44·7	32·4
Silt . . .	13·3	34·0	58·6	23·4	8·7	16·0	7·0
Clay . . .	81·7	39·9	29·9	23·4	28·8	18·3	8·6
Organic Carbon .	1·1	3·35	3·1	3·2	1·9	3·7	2·45
Organic Matter (Org. C × 1·724)	1·9	5·8	5·3	5·5	3·3	6·4	4·2
Loss on Ignition .	9·4	11·2	10·3	10·8	5·0	9·0	5·5

The mechanical composition of soils may be represented graphically by means of *summation curves*, in which the ordinates are the summation percentages of the fractions and the abscissae the particle diameters. In Fig. 4 the analyses given in the table are thus represented. The way in which the curves are made may be seen from the curve for a heavy loam. The first point on the curve is given by the ordinate 39·9, the clay percentage, and the abscissa 0·002 mm. For convenience of representation the particle diameters are shown on a logarithmic scale, the successive intervals being 0·002—0·02—0·2—2·0. The ordinate for the next point is obtained by adding together the percentages of clay and silt, giving 73·9, the corresponding abscissa being 0·02. This means that 73·9 per cent. of the material has diameter less than 0·02 mm. The ordinate for the third point is given by 39·9 + 34·0 + 17·8 = 91·7 and the abscissa is 0·2. Since all the material has diameter less than 2·0 mm., the last point is at 100 and 2·0. The points are then joined by a smooth curve. From determinations made with a variety of soils, it has been shown that if the soil is subdivided into a larger number of fractions, the experimental points still lie on smooth curves. It should be noted that diameters below 0·2 mm. are equivalent diameters, i.e. they refer to separations based on settling velocities, assuming Stokes's Law.

The general form of the curves is similar. The curves for the heavy silt loam and for the medium loam (Herts) are of interest because they clearly consist of two parts, suggesting a mixture of material. This is in agreement with the supposition that the soil is composed of a chemically weathered range of finer fractions and a mechanically weathered range of coarser fractions. The heavy clay soil would appear to consist almost entirely of the former class of material, whilst the loamy sand consists mainly of the other.

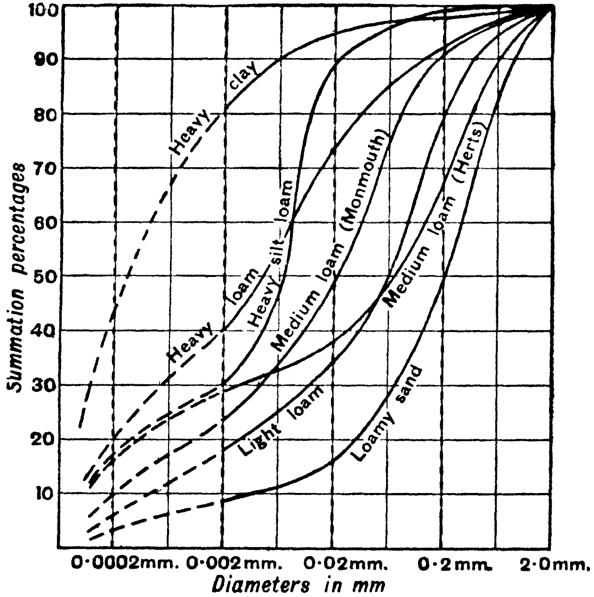


FIG. 4.—Mechanical Composition Curves.

The broken curves below 0·002 mm. represent their probable course, tending towards a lower limit of particle size at about 0·00005 mm. This, of course, is only inferred from settling velocities and does not represent an actual particle size.

Clay.—So far as the mineral part of the soil is concerned, the clay has the most important part in controlling its physical and chemical properties. The coarser fractions, both physically and chemically, generally play the part of a relatively inert skeleton or framework for the more reactive clay fraction. This is not invariably true, for there are some soils whose coarser fractions have considerable reactivity. As a rule, however, the reactivity of the soil is seated in the clay fraction.

We have seen that in the chemical weathering of rock minerals secondary products are formed which we may for convenience call the weathering complex. For most soils we may assume that the weathering complex is practically identical with the clay fraction recognized in mechanical analysis. This is not strictly true, because fragments of unweathered minerals occur in the clay fraction, whilst on the other hand, secondary material may occur in the coarser fractions : but for most purposes the weathering complex may be studied in the clay fraction. Further, insofar as a distinction can be drawn between the reactive and the non-reactive fractions of the mineral soil, the limit assigned for the clay fraction in mechanical analysis is probably the most satisfactory separation. It should be realized, however, that since chemical reactivity is closely correlated with specific surface, the finer fractions of the silt must possess appreciable reactivity.

We may now consider briefly the properties of the clay fraction. In the first place, we note the enormous specific surface. This can be understood from the following considerations. If we take a cube of 1 cm. side, its total surface will be 6 cm.^2. If the 1 cm. cube is now divided into cubes of one-tenth the size, i.e. into cubes of 0·1 cm. side, we shall have 1,000 cubes, each with a surface area of 0·06 cm.^2, so that the total area will now be 60 cm.^2. As a general rule, we may say that the specific surface, i.e. the total area per unit weight, varies inversely as the particle size. It may be calculated that 1 gram of spherical particles of diameter 0·002 mm. has a total area of 11,320 $cm.^2$. But the clay fraction includes a range of particles varying in diameter from 0·002 mm. down to about 0·00005 mm., and by calculation it may be shown that the total area of 1 gram of a typical clay fraction has a total area of approximately 200,000 $cm.^2$. These figures are only estimates and are based on the assumption that the particles are spherical, whereas they are mainly platy or needle-shaped. They serve to show the order of magnitude of the surfaces involved. It can be readily seen that the surface development in the clay fraction is very great. Indeed, by far the greater part of the surface in ordinary soils is associated with the clay fraction.

Clay has certain properties associated with colloids, such as gelatine and agar. One of the most important is the property of taking up water. A fragment of dry clay fraction placed in water absorbs water and swells up in so doing. This property is shown by the clay in a natural soil, and it is well known that clay soils have a great capacity for taking up water, and that they swell on being wetted and contract on drying This latter effect can be well seen during periods of drought in a clay country, where wide cracks, often extending several feet down can be seen in pastures. This expansion and contraction with changes in moisture content has an important bearing on the structure and tillage properties of soils.

Clay, like other colloidal materials has cohesive and adhesive properties. The presence of clay in the soil enables the aggregation of the fine particles into compound particles or crumbs. It also makes possible the formation of coarse clods which, on drying out set very hard and make the tillage of clay soils so difficult. Closely connected with cohesion and adhesion is plasticity. Soils containing appreciable proportions of clay are plastic when moist, i.e. they can be worked or kneaded and retain the form impressed on them like putty or pitch. Whilst this property is very desirable in a modelling clay, it is an inconvenient property in an agricultural soil, and therefore clay soils cannot be cultivated when they are sufficiently moist to be plastic.

Clay is the most chemically reactive constituent of the mineral part of the soil. It behaves as a weak insoluble acid and can combine with bases. In an ordinary fertile soil, the clay acid is more or less neutralized by bases, principally calcium, with smaller proportions of magnesium, potassium, and sodium. The bases thus combined are termed exchangeable bases, because, if the soil is treated with a salt solution, e.g. ammonium chloride, the bases in the soil are displaced by the base in the salt solution. In this case ammonium enters the soil, and calcium, magnesium, sodium, and potassium go into solution as chlorides. In a humid climate, particularly under certain types of vegetation, the exchangeable bases are lost from the soil and the soil becomes acid, in other words it becomes a hydrogen soil.

In addition to the acid or potentially acid properties of the clay, weak basic properties are also shown. One of these properties is anionic exchange, which is analogous to base exchange just described, except that instead of exchangeable bases, exchangeable acid radicles are displaced. Some soils can give up appreciable amounts of phosphate by anionic exchange. In sesquioxidic clays, i.e. clays rich in alumina or ferric oxide, anionic exchange may be of considerable importance. Such soils have a high capacity of absorbing phosphate, and may even fix nitrates, sulphates, and chlorides, which are not absorbed by ordinary soils.

There is an important difference between clays rich in silica and those rich in sesquioxides. The siliceous clays have the colloidal properties more strongly developed than the sesquioxidic clays. A soil with 30 or 40 per cent. of siliceous clay is definitely a heavy soil and difficult to work, whilst a soil such as many in the tropics with the same proportion of sesquioxidic clay is friable and easy to work.

An important property of clay connected with its colloidal character is its power of flocculating or coagulating when in aqueous suspension under the action of minute quantities of various salts. To illustrate this point, a few grams of good clay should be rubbed up with several litres of distilled water and the supernatant turbid liquid poured off into a series of tall jars each holding from 300 to 500 c.c. of the liquid. To one of these jars nothing is added, to two others 0·018 and 0·009 gram of hydrochloric acid respectively, to a fourth 0·028 gram of calcium chloride, and to the fifth 0·58 gram of sodium chloride. The contents of the jars are shaken up until solution is effected, and they are then put aside to stand. After some time the liquids to which the salts have been added will begin to clear, and the clay particles will clot together and fall to the bottom ; the jar containing the larger quantity of hydrochloric acid will clear the first, the others will clear approximately together, but the pure clay water will remain turbid for many days. If a little of the turbid clay water be examined by a $\frac{1}{12}$-inch oil immersion lens under the microscope, it is just possible to see the clay particles in rapid " Brownian " motion, and if a little acid or salt be then introduced under the cover glass, they will be seen to move together and form into little clots or aggregates as soon as they experience the effect of the added acid or salt. By comparative experiments it can be shown that the flocculating power of any salt is proportional to its amount up to a certain limit, when the material is so completely flocculated that no further addition of salt has any effect ; conversely, the flocculating power of a given amount of salt is inversely proportional to the quantity of clay suspended in the liquid. The flocculating power of a salt also varies with both the acid and the metal ; the following table shows approximately their comparative effect :

HCl	30	HNO_3	28	H_2SO_4	20
$CaCl_2$	15	$Ca(NO_3)_2$	10	$CaSO_4$	>5
KCl	3	KNO_3	>2	K_2SO_4	<1
$NaCl$	>1	$NaNO_3$	<1	Na_2SO_4	0·5

The alkalis and salts like sodium phosphate, which give rise to free alkalis on hydrolysis, instead of flocculating have the opposite effect, and keep the particles in their finest state of division without any tendency to settle.

Flocculation and deflocculation have their counterpart in the behaviour of clay under field conditions. The mechanism is somewhat different, because the changes take place, not in a weak aqueous suspension but in the soil system, which is mainly solid material Under these conditions we have as analogous processes crumb formation and loss of structure or puddling. Crumb formation, the aggregation of the particles of the soil into crumbs is favoured by the same reagents that cause flocculation in dilute suspensions. The reverse process, puddling or loss of structure, is also favoured by those reagents that cause deflocculation in dilute suspensions.

The behaviour of soil depends not only on the presence of colloids, but also on their chemical composition. Soils devoid of colloidal material cannot exhibit crumb formation. Such soils, if very fine in texture present great difficulties in cultivation, owing to their inability to form crumbs. The behaviour of the clay colloids themselves is greatly affected by the bases with which they are combined. In normal soils, the predominant base is calcium, but cases occur where sodium is present in appreciable proportions. Sodium clays have a high capacity for taking up water, forming a sticky impervious mass, which readily disperses in water, giving a turbid suspension.

The power of crumb formation plays a very important part in the cultivation of clay soils. When such a soil possesses a good texture its finest particles are in a state of temporary aggregation, so that they behave as if the soil, as a whole, were built up of much coarser particles. Just as a potter or a brickmaker brings his material into its highest condition of plasticity by repeatedly kneading and working it, by which process the naturally formed aggregates are resolved into their ultimate particles and the material is made as fine-grained as possible, so if a clay soil be in any way worked or disturbed when in a wet condition, it becomes apparently more clayey than before. It remains persistently wet and impervious to the percolation of water and shrinks when dry into hard tenacious clods. But if the clay be exposed to the weather for some time, so that it undergoes alternations of temperature, freezing and thawing, wetting and drying, it will experience a certain amount of spontaneous crumb formation and behave as though it were coarser grained, so that if caught in the right state of partial dryness it may easily be crumbled. As the colloid particles dry they shrink and lose water which they do not entirely reimbibe when they are moistened again. Moreover, the shrinkage necessarily draws air in among the particles, and this air is not expelled on rewetting, so that the texture is altered in the direction of a crumb structure.

Crumb formation may also be aided or otherwise by the use of certain artificial manures, as will be explained later ; again, the incorporation of humus much improves the texture, whilst the action of lime is particularly effective and is much employed in practice to ameliorate the working of clay soils.

Lime itself can be shown in the laboratory to possess little flocculating power, for though its base is calcium, a highly effective base in producing a firm gel, the hydroxyl ions of the hydroxide, which is the solution of lime in water, possess a dispersive or deflocculating effect upon the particles. However, as soon as lime is applied to the soil it becomes converted into carbonate, and some of it will be always going into solution as calcium bicarbonate, a salt which possesses great flocculating power.

In practice, the application of such small quantities of lime as a ton or even half a ton to the acre have the greatest value in ameliorating the working of clay land ; not only does it move more readily and fall more easily into a good tilth, but by becoming coarser grained it allows the rain to percolate more freely and thus dries earlier in the season, so that the limed land can often be worked several days before the unlimed land can be touched. Though the Rothamsted soil is by no means of the heaviest, it is only because of the repeated additions of carbonate of lime in former years that it can be retained under arable cultivation ; portions of the same land without carbonate of lime lie so wet in the spring that they were laid down to grass in consequence of the repeated failures to secure a good seed-bed.

Calcium carbonate, although present in many soils is not a necessary constituent, in the same way that clay and humus are essential ingredients. Although a certain proportion of lime in the soil is necessary for fertility, it is effective if combined with clay and humus and need not be present as free calcium carbonate. Although most British soils do not contain calcium carbonate naturally, there are great areas of soil in the south and east, notably the Chalk and Oolite soils that contain calcium carbonate as an original constituent. The proportion varies enormously, and may rise as high as 60 per cent. in shallow chalk soils, but in the majority of soils where it occurs, the proportion is less than 10 per cent. It is essentially a transitory constituent, as it is constantly removed by the action of percolating water charged with carbon dioxide. The annual loss of lime in this way may amount to as much as 500 pounds of lime per acre. Indeed, it is difficult to understand how any of it persists in the surface layers of many soils, were there not some compensating agencies at work. Amongst these must be reckoned the calcium salts in plants, which in many cases are drawn up by deep roots from the subsoil and become calcium carbonate on the ultimate decay of the plant residues.

In a normal soil the particles of calcium carbonate vary in size, many of the finer particles of silt and clay being loosely cemented together by calcium carbonate.

Humus.—On examining many rocks taken from such depths that they have undergone none of the weathering processes which convert them into soil, they are found to contain both carbon and nitrogen, occasionally in quantities comparable with those found in the soil itself. This is only the case with the sedimentary rocks and particularly with indurated clays ; the carbon and nitrogen in fact only represent the organic matter in the original deposit in a more or less mineralized condition. But since these carbon and nitrogen compounds are only slightly affected by any of the weathering processes by which soil is made, they must pass into the soil and there become merged with the organic matter of more recent origin. Such material, however, plays a very unimportant part in the soil, and we may pass on at once to the débris of vegetation of recent origin or the humus which is characteristic of all soils proper.

The term humus is applied to the black or dark brown material of vegetable origin which gives to surface soil its characteristic darker colour as compared with the subsoil. It is essentially a product of bacterial action. There are a number of bacteria working in the absence of air and universally distributed, which attack the carbon compounds of plant tissues, especially the carbohydrates, with the production of marsh gas or hydrogen, carbonic acid, and humus. In the presence of air the characteristic humus-forming fermentation is continued by one which results in the complete combustion of the organic matter to carbonic acid. For this reason more humus is found in a pasture than in a continually aerated arable soil, more again in clays than in the lighter soils through which air is always being drawn as the rain percolates, and the accumulation of humus reaches its maximum where considerable rainfall and an impermeable stratum combine to make the soil so water-logged that all access of air is cut off, as in swamps and bogs. The presence of chalk in the soil also assists in the destruction of humus, since it neutralizes the acids which largely compose the humus, and which tend to inhibit the further action of bacteria.

The chemical composition of humus is indefinite ; it is a variable mixture of several substances, themselves of very complex constitution ; it always contains more carbon and less hydrogen and oxygen than the vegetable tissues from which it was formed. The following figures show the composition of grass and of the top brown layer of turf in a peat bog, also of the same peat of greater age at depths of 7 and 14 feet, the mineral matter and moisture being excluded in calculation in each case :

	Grass.	Top Turf.	Peat at 7′.	Peat at 14′.
Carbon . .	50·3	57·8	62	64
Hydrogen . .	5·5	5·4	5·2	5
Oxygen . .	42·3	36	30·7	26·8
Nitrogen . .	1·8	0·8	2·1	4·1

Substances akin to humus can be formed from the carbohydrates (such as sugar, starch, and cellulose), by heating them for some time with water under pressure, the action being more rapid if a trace of mineral acid be present ; the resulting substances are weak acids and form salts, so are generally termed humic acid :

	Humic Acid.	
	From Sugar.	Natural.
Carbon . .	63·9	56·3 to 59
Hydrogen . .	4·6	4·4 „ 4·9
Oxygen . .	31·5	32·7 „ 36
Nitrogen . .	...	2·8 „ 3·6

As a rule, the active humus of the soil is there present in the form of salts of calcium, which on treatment of the soil with dilute hydrochloric acid are decomposed, a little of the humic acids going into solution but the greater part remaining undissolved. By filtering off the acid and then treating the soil with a weak solution of ammonia or other alkali, the liberated humic acids are dissolved and may be precipitated either as free acids by the addition of hydrochloric acid, or as calcium salts by the addition of a solution of calcium chloride. The humic acids thus going into solution are sometimes estimated as "soluble humus" : they do not include the whole of either the organic matter or the nitrogen in the soil. The brown solution that is formed is akin to the dark liquid draining from a dung heap, which contains humus dissolved by the alkaline carbonates of the fermented urine.

In humid climates, such as our own, soils are found which naturally possess an acid reaction, and in which the whole or part of the soluble humus is uncombined with calcium. In practice a sharp distinction can be drawn between the acid humus of the upland moors and peat bogs, formed where the water contains no mineral bases, and the neutral humus of the black soils of the Fens, formed from vegetation that has decayed in water containing calcium carbonate. The latter is much more subject to further changes on aeration and in cultivation gradually yields to plants the nitrogen it contains.

Although dark brown humic substances can be prepared from carbohydrates, and therefore contain only carbon, hydrogen and oxygen, yet the soluble humus of the soil, even when dissolved and reprecipitated, always contains some nitrogen, nor can it be obtained entirely free from phosphorus and mineral matter. The original vegetable matter is made up not only of carbohydrates, but of other carbon compounds containing nitrogen, and in some cases both nitrogen and phosphorus; these all break down under bacterial action into dark-coloured substances richer in carbon, and roughly classed as humus. The splitting-up process continues in the soil, so that humus becomes one of the sources of nitrogen for the food of the plants.

During the formation and continued decomposition of humus the carbohydrates appear to be first attacked, and the nitrogen-containing bodies, e.g., the nucleins in particular, resist the action of bacteria. For this reason, as the organic matter content of the soil falls, the proportion of nitrogen in the humus itself tends to increase, the decomposition falling more heavily on the purely carbonaceous part of the material.

This is seen in the figures obtained by Lawes and Gilbert for the ratio that exists between the proportions of carbon and nitrogen in various soils:

RATIO $\frac{C}{N}$.

Cereal Roots and Stubble	43
Leguminous Stubble	23
Dung	18
Very old Grass Land	13·7
Manitoba Prairie Soils	13
Pasture recently laid down	11·7
Arable Soil	10·1
Clay Subsoil	6

For a given soil, there appears to be a characteristic carbon-nitrogen ratio. If plant residues or other organic matter with a wider ratio is added to the soil the losses fall mainly on the carbonaceous part of the material, until a residue is left approximating in composition to that of the soil organic matter. The widest ratios are found in moorland and heath soils, with much raw fibrous material in the surface layers. The ratio decreases generally in going down the profile. There is a tendency for soils of warm climates to have narrower ratios than soils of cold and temperate climates, but this rule is not invariable. Nor is there any close correlation between carbon-nitrogen ratio and soil fertility. A carbon-nitrogen ratio of about 10 is usual for British soils.

Like clay, humus is a colloid. It has to an even greater degree than clay the property of imbibing water and expanding in so doing. Like clay, humus can give cohesion to soils and is particularly valuable in giving stability to loose sandy soils. Unlike clay, however, humus does not confer plastic properties on soils. Its effect on texture is wholly favourable because it promotes crumb formation in clay soils, thus rendering them more open in structure, whilst it increases the water-holding capacity of light soils and at the same time gives them cohesion.

Soil Solution

By soil solution is understood the moisture present in the soil under ordinary field conditions. Since it is this moisture that furnishes the water supply and the food supply for plant roots, a knowledge of its composition and behaviour is of some importance. Unfortunately, it is by no means easy to isolate it unchanged from the soil. Small quantities of soil solution can be obtained from very moist soils by pressure, but at moderate or low moisture contents, this method is inappropriate. Most of the methods used, therefore, depend on displacement of the soil solution from a column of soil, either by an inert liquid or else by water. During recent years, a variant of the pressure method has been employed in which the soil is placed on a suitable filter and the moisture driven out by air pressure.

The composition of the soil solution varies enormously and may vary in the same soil at different seasons of the year.

The following figures obtained by Burd and Martin in California are typical:

Date.	Parts per million in displaced solution.								
	NO_3.	HCO_3.	SO_4.	PO_4.	Ca.	Mg.	Na.	K.	Total Solids.
30/4/1923 .	149	83	561	8·1	242	91	42	21	1190
4/9/1923 .	58	135	432	0·6	193	47	40	9	935

The decrease in concentration following the growth of a crop can be seen.

Although the importance of the soil solution for the nutrition of crops is evident, little progress has been made in correlating the composition of the soil solution with the actual plant nutrient status of soils. For example, it has not yet proved possible from an examination of the soil solution to forecast the probable manurial requirements of crops.

Soil Air

The air within the soil differs from the atmosphere above the soil in many respects. In the first place, under ordinary conditions, it is saturated with water vapour. Only in the upper layers during drought does the soil air fall below vapour saturation. In arid countries the soil air may be unsaturated for long periods of the year to a considerable depth, depending on the extent to which the soil is dried out. Secondly, the soil air is considerably richer in carbon dioxide than the atmosphere. The actual concentration varies with root activity and on the amount of decomposable organic matter present, and on the rate of biological oxidation. Other things being equal, pasture soils are richer in carbon dioxide than arable soils, but heavy dressings of farmyard manure applied to arable soils may result in a rapid evolution of carbon dioxide and a considerable rise in the carbon dioxide concentration in the soil air. Conditions favouring biological oxidation lead to an increase in soil carbon dioxide. The air of pasture soil may contain up to 1·5 per cent. of carbon dioxide, whilst that of arable soil rarely contains more than 0·5 per cent.

CHAPTER IV

STRUCTURE AND TILLAGE PROPERTIES OF SOILS

Meaning of Structure and Conditions by which it is affected—Pore Space and Density of Soils—Soil Structure and its Characterization; Effect of Organic Matter on Structure; Effect of Cultivation on Structure—Types of Structure—Plasticity and Cohesion.

IN the preceding chapter, the nature of the particles composing the soil has been discussed; it now remains to consider the manner in which they may be arranged, and the structure that results from the interaction of the soil particles, the water, and such salts as may be dissolved in the water. On these factors depend the tillage properties of the soil, i.e. the degree of resistance it affords to the passage of a plough, etc., the ease or otherwise with which that prime object of cultivation, the preparation of a seed-bed, can be attained.

Pore Space and Density of Soils

It is clear that as a soil consists of particles, there must be between them a certain amount of space which is occupied by air or water; this is known as the "pore space," and on its amount will largely depend the density of the soil. Taking the simplest theoretical case, a soil made up of equal spheres in contact with one another, it will be found that the pore space is dependent upon the method of packing, but not upon the size of the spheres. If the system of packing shown in A and B, Fig. 5, is adopted, the pore space reaches its maximum and amounts to 47·64 per cent. of the whole volume occupied by the soil; this proportion is the same

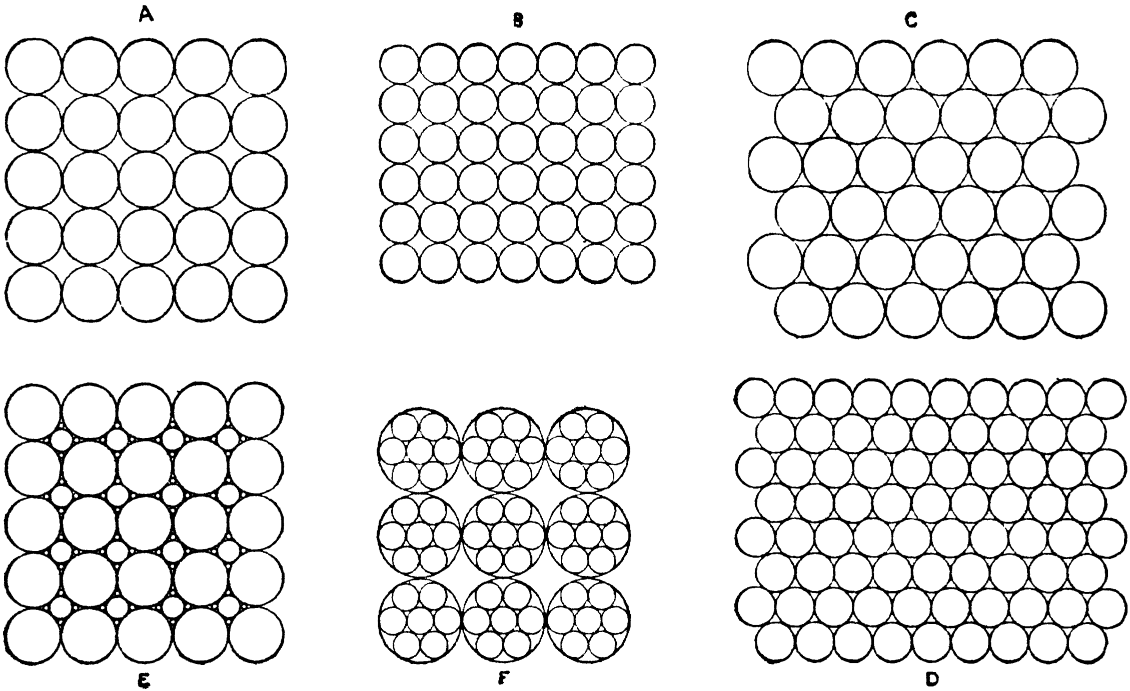


FIG. 5.—Diagram illustrating Pore Space between Spherical Particles.

when the soil particles have a smaller diameter, as in B; as long as the spheres are uniform in size, whatever that may be, and are packed as shown in the diagram, the pore space will be at its maximum. The minimum pore space is attained by the packing shown in C and D; it amounts to 25·95 per cent., and is again independent of the size of the particles, provided they are uniform. If the spheres are, however, of very different sizes, so that smaller spheres lie wholly within the spaces between the larger spheres, as in the arrangement shown in E, the pore space may be indefinitely reduced. On the other hand, if aggregates of particles exist in the soil, containing both pore space between the ultimate particles and between the aggregates which behave as single particles, as in F, the pore space may rise above the maximum of 49 per cent. A soil *in situ* generally possesses a pore space larger than the proportions indicated above; various causes, such as the stirring due to cultivation, the decay of vegetation, etc., leave definite cavities in the soil: for example, if a hole be dug for any purpose in ordinary cultivated ground and afterwards filled up with its own soil, it is rarely possible to fill the hole completely, especially if a little pressure has been used to trample down each layer.

In ordinary soils the pore space varies from a little over 50 per cent. among the stiff clays, down to 25 or 30 per cent. in the case of coarse sands of uniform texture. The reason for the greater pore space with the finer-grained soils lies in the fact that the weight of the small particles of clay is not sufficient to overcome the friction and move the particles into the arrangement giving the minimum pore space. If some small shot are shaken into a graduated measure and the pore space determined by pouring in a measured volume of water, the indicated minimum will be found; but if the experiment be repeated with sand that has been sifted to get approximately a uniform size, a higher figure will result. In the one case the particles are too light to exert much force towards the rearrangement of the mass; in the former case the heavy smooth shot slip straightway into the most compact arrangement, because by it the shot attain their lowest position. In consequence of the pore space, the density of a soil *in situ* will differ very much from that of the materials of which it is composed, nor will all soils possess the same apparent density when dry. Perhaps the best way of ascertaining the apparent density of a soil or soil materials is to get a smooth metal pint pot or like measure, fill it with the material in question with gentle tapping, and then strike off the upper surface smooth with a rule. The weight of the contents divided by the volume gives the apparent density, from which the true volume and the pore space can be calculated, if the true density of the material be known.

The percentage pore space may be calculated as follows. Let D be the true density of the material and d the apparent density. The weight of 100 c.c. of the material will be $100\ d$, and its true volume $100d/D$. The percentage pore space will therefore be $100-100d/D$, or $100(D-d)/d$. As a first approximation we may take the true density of the mineral portion of the soil as 2·7, the true density of humus as 1·2, and the true density of the whole soil as 2·5. The true density of highly organic soils will be less, and in the case of peats will approximate to that of humus.

The following table shows a few determinations made in the laboratory, of the apparent density of various soils in a roughly powdered state and without the stones, which, being solid, would add to the apparent density of the soil. The results are also recalculated to show the weight of a cubic foot of the soil, and the weight per acre of a layer 9 inches deep. In the last column the percentage pore space is given,

	Apparent Density.	Weight per cubic foot.	Lbs. per acre to 9″.	Percentage Pore Space.
Heavy Clay . .	1·062	66·4	2,150,000	57
Sandy Clay . .	1·279	80	2,600,000	49
Sandy Clay Subsoil .	1·18	73·7	2,380,000	53
Light Loam . .	1·222	76·4	2,480,000	51
Light Loam Subsoil .	1·144	71·5	2,320,000	54
Sandy Loam . .	1·225	76·7	2,490,000	51
Sandy Peat . .	0·782	49	1,580,000	68·5
Light Sand . .	1·266	79·2	2,560,000	49

calculated on the assumption that the true density of the soil is 2·5.

The figures given above are not exactly comparable with soils under natural conditions, because of the powdering, the exclusion of stones, etc., but they serve to show that the clay soils usually described as " heavy " are really less dense, and weigh less per cubic foot than some of the lighter soils, whereas pure sands are the densest of all. The farmer's terms of " light " and " heavy " land refer to the draught of the plough, the resistance the soil opposes to being torn asunder, and not to the actual weight of the portion moved ; sands which he calls " light " being, as the table shows, heavier per cubic foot than the clays which the farmer calls heavy soils.

This point will be further elucidated by the following table, which shows the weight per cubic foot of the arable soils at Rothamsted and Woburn down to a depth of 3 feet. These results represent the real weights of the soil as obtained by cutting out a block 6 inches square by 9 inches deep, weighing it, and afterwards ascertaining the deduction to be made for water. The Rothamsted soil is a stiff clay with many flints, the Woburn soil is a loose, coarse-grained sand, containing only a little stone derived from the rock below. It will be seen that if the stones are excluded the density increases with the depth, because of the greater consolidation caused by the weight above and to some extent by the washing down of the finest particles, but the increase does not continue much below the depth of 3 feet, the limit of these measurements :

		Weight per cub. foot.	Per cent. of Stones.	Weight per Acre.
		Lbs.		Lbs.
Rothamsted Arable Broadbalk	0″ to 9″ .	95·4	16·8	3,116,000
	9″ „ 18″ .	93·0	12·0	3,037,000
	18″ „ 27″ .	92·0	7·1	3,004,000
	27″ „ 36″ .	92·2	7·5	3,012,000
Woburn Arable	0″ „ 9″ .	96·6	2·96	3,157,000
	9″ „ 18″ .	103·8	5·95	3,382,000
	18″ „ 27″ .	106·2	4·92	3,462,000
	27″ „ 36″ .	106·9	7·83	3,501,000

From the data thus obtained as to density and pore space, together with a mechanical analysis to show the proportion of particles of various sizes, it is possible to calculate for any given soil both the number of soil particles and the area of the surface they expose, on the assumption that the particles are spherical. Approximately, with grains 1 mm. in diameter, there would be 700 grains in 1 gram of the soil, and the number of grains to the gram will vary inversely as the third power of the diameter, i.e., if the diameter be divided by 10 and become 0·1 mm., there will then be 700,000 grains to the gram. The surface possessed by all the soil grains can be similarly deduced by calculation, and will be found to vary inversely as the diameter of the individual grains ; a sphere 1 inch in diameter will have only half the surface of the eight spheres of half an inch in diameter that occupy the same volume. Hence it follows that the total surface of the particles of unit weight of an ordinary soil must be very great, and since many of the properties of the soil are dependent upon the surface, it becomes important to arrive at some measure of this quantity. By calculation, only a very rough idea of its extent can be formed, both because every departure of the soil grains from the spherical form will increase the surface without affecting the weight, and also because the mechanical analysis of a soil gives only a generalized statement of the distribution of soil particles of various sizes in the soil. But the surface of the soil grains in the case of a sandy soil where the grains are all free, may be calculated from the observed rates of flow of fluids like air or water through a measured portion of the sand ; and by using this method King has computed the surface of the constituent particles of various types of soil with the results set out on page 63.

As a rough figure to remember, the surface of the particles in one cubic foot of an ordinary light loam may be taken as about an acre ; this will increase as the soil approaches more and more to clay, and diminish as the soil becomes increasingly sandy. The extent of surface exposed by the soil particles is important because it is their active part ; other conditions

	Pore Space, per cent.	Area of Surface in square feet, per cubic foot of Soil.
Finest Clay	52·9	173,700
Fine Clay Soil	48	110,500
Loamy Clay Soil	49·2	70,500
Loam	44·1	46,500
Sandy Loam	38·8	36,900
Sandy Soil	32·5	11,000

being equal, the amount dissolved from a solid body in a given time by any solvent will be proportional to the surface exposed.

Soil Structure

Every farmer realizes the practical importance of a good structure. This is what is commonly understood by the term *tilth.* The structure of the soil dominates the water-air relationships of the soil and its behaviour under tillage. Yet, although its importance is recognized both by the farmer and the scientist, structure is exceedingly difficult to define and to measure.

Structure in the soil is rendered possible by the presence of colloidal material, which serves to bind the fine particles of the soil into compound aggregates or crumbs. A soil devoid of colloidal material cannot aggregate and its particles exist independently of each other in the so-called single-grain structure. In the case of sandy soils, this in itself is not a serious drawback because, owing to the size of the particles the spaces between them are sufficiently large to admit movement of air and water. If the soil is very fine grained as in certain silts, the particles can pack very closely together, giving a low pore space and a low permeability to air and water. This is well seen in certain soils which form a steely compact surface after heavy rain.

The problem of soil structure has been approached in the past through the study of flocculation. It is well known that when small quantities of electrolytes, e.g. hydrochloric acid or calcium chloride are added to a turbid suspension of clay, a kind of aggregation, known as flocculation takes place, and the small aggregates thus formed settle out leaving a clear liquid. Clay soils can be flocculated and yet have a poor structure, for the aggregates are so small that they pack closely together forming an impermeable mass. For a soil to have a good structure the aggregates must be comparatively coarse with spaces between them sufficiently large to permit free movement of water and air. The actual arrangement of the aggregates is also a factor. This may be illustrated by analogy with a load of porous bricks. If the bricks are laid or fitted close together, the interstitial spaces will be very small, whereas if they are dumped in a heap the spaces will be quite large. The desirable structure should resemble this arrangement rather than that of the closely laid bricks.

Many methods have been proposed for characterizing the structure of soils. In one group of methods, the objective has been to determine the percentage distribution of the different sized aggregates, in effect, to carry out a mechanical analysis without a preliminary dispersion. These aggregate analysis methods divide themselves into dry sieving and wet sieving methods. Both types of method are beset with the fundamental difficulty of standardization of procedure.

In the dry sieving methods, the soil is placed on a " nest " of sieves so arranged that the material passing the coarsest sieve falls on to the next coarsest sieve, and so on. The whole system is shaken and the amount retained on each sieve is determined. It is obvious that very different results can be obtained according to the vigour with which the soil is agitated on the sieves and according to the time of shaking. Aggregates that resist a moderate agitation would be broken by a more vigorous agitation. The variability due to this may be seen from the following results of E. W. Russell and

	Percentage Soil on Sieve.		
Sieve size.	*Team A.*	*Team B.*	*Team C.*
1½ in.	15·5	9·6	11·6
⅝ in.	17·9	14·1	20·9
¼ in.	16·5	17·0	25·3
3 mm.	25·4	26·6	31·6
Passing 3 mm.	24·7	32·6	10·7

R. V. Tamhane, in which three sets of workers independently carried out a sieve analysis on the same soil.

It is obvious that the results are very discordant and that reproducible figures can only be obtained by rigid standardization of the shaking technique. It is also necessary to prescribe the moisture content at which the sieving shall be made, as is shown by the following figures obtained by the same workers on the same soil at different moisture contents :

	Percentage on	*Sieve at Moisture*	*Contents on*
Sieve size.	*19 per cent.*	*15 per cent.*	*0 per cent.*
1½ in.	19·5	29·5	16·0
⅝ in.	25·5	30·5	32·0
½ in.	25·0	16·0	21·0
3 mm.	24·5	15·5	20·0
Passing 3 mm.	4·5	8·0	11·0

Similar difficulties beset the determination of aggregate size distribution in the wet sieving methods. Different results can be obtained according to whether the sample is giving preliminary dispersive treatment or not and according to the time and vigour of shaking.

The position with regard to aggregate analysis, therefore, is that although the formation of aggregates in the soil is recognized to be desirable, there is no generally established method for their quantitative determination. There is, it is true, a wide choice of proposed methods, each of which may give a useful comparison among a limited selection of soils, but all of them are largely conventional and the conditions of separation and even the type of apparatus must be described in every detail. This would be no drawback if general agreement could be reached as to the method, and it may be hoped that in the future, the necessary national or international co-operation may be taken to establish such a method, following the precedent of the International method for mechanical analysis. Some preliminary steps had, in fact, been taken by the International Society of Soil Science before the outbreak of the present war.

Important differences exist in the character of the structural aggregates. We may distinguish loose aggregates, owing their existence to simple cohesion or the tension of thin films of moisture, and true aggregates held together by the soil colloids. The loose aggregates are of a temporary character and owe their existence to the operations of cultivation, frost, and root action.

The extent to which soils are formed into true aggregates may be determined by carrying out a mechanical analysis by water dispersion and comparing the percentage of clay obtained with that obtained by complete dispersion. The *structure factor* is then given by the difference between the two figures expressed as a percentage of the clay by complete dispersion.

An entirely different and possibly better line of attack on the problem of soil structure determinations is the study of pore-size distribution. Just as there are particles and aggregates of all sizes in the soil, so there is also a range of pore-size. At a given moisture content, a certain negative pressure is required to withdraw water from the soil : this is known as the suction pressure. By plotting suction pressure against moisture content, it is possible to form an idea of the distribution of the different sized pore spaces present. This is probably a better approach to the problem than aggregate analysis, because it is by virtue of its pore-size distribution and not by the actual size of the aggregates that one soil has a better structure than another. Reverting to the analogy of the load of bricks, the aggregate analysis should be the same whether the bricks were laid or dumped, but the pore-size distribution would be quite different in each case..

✓The encouragement and maintenance of a good structure is of the highest importance for practice. The first condition for the existence of structure is the presence of colloidal material. In this connexion, the behaviour of clay differs somewhat from that of humus. The aggregates formed by clay are generally harder than those in which humus is the predominant colloid. In virgin soils and in grassland soils, there is probably a tendency for humus recently formed from plant residues to be deposited on the surface of the structural aggregates, which are thereby rendered more stable.

A good lime-status is commonly supposed to favour structure formation. The effect is not, however, clearly understood. In soil deficient in organic matter, the effect of lime on structure is not always favourable. In the presence of decomposable organic matter, lime has a generally favourable effect on structure. It may also have an indirect effect, by increasing plant growth and, consequently, the addition of organic matter to the soil. When grassland soils are brought under the plough, a good lime-status is necessary for the decomposition of the old turf. Fresh organic matter, i.e. organic matter capable of decomposing to form humus encourages good structure, particularly where this decomposition is assisted by a good lime-status.

Soils that have long been under natural vegetation or under grass or prairie always show a good structure when first brought into cultivation, provided the lime-status is satisfactory. It is to be regretted that much of the poor grassland ploughed up during recent years does not fulfil this latter condition. Dressings of farmyard manure are of the greatest value in assisting in the development of a good structure. Indeed, this may be one of the principal effects of farmyard manure. It can be well seen in an old garden soil, particularly in certain clay districts, where the mellow structure of the garden can be compared with the poorer structure of adjacent old arable soils in the fields.

The general effect of cultivation is to improve structure. The level of freshly ploughed land is always higher than that of the adjacent undisturbed soil. During the time the land has been under crop, it has been settling down and the pore space has steadily decreased. When the land is ploughed, the pore space is increased, the increase being mainly in the larger interstices. Subsequent cultivation breaks down the larger aggregates, with the final production of a fine tilth for the seed bed, consisting of medium and small-sized aggregates. Frost has a good effect in making the soil more friable and in breaking up compacted structural units, particularly when it acts on land roughly ploughed in the autumn or early winter. Alternate wetting and drying, acting on a bare fallow, has a similar effect in mellowing the tilth.

Structure may be partially destroyed by mechanical means such as trampling. This may be seen in the vicinity of gates and along cart-tracks in fields. The same effect may be produced on certain types of soil by beating rain.

The effect of most fertilizers on structure is either negative or favourable. In the case of nitrate of soda, however, excessive use may have undesirable consequences. The replacement of calcium by sodium in the absorbing complex leads to a breakdown of aggregates. This is well shown by plots at Rothamsted that have received annual dressings of nitrate of soda. The tile drains beneath them always run turbid with suspended clay. Over a long period this has resulted in such a loss of clay that there has been a decrease in the clay content as shown by mechanical analysis. The soil is also more sticky and intractable in wet weather.

Similar harmful effects on structure may be seen where land is flooded by sea water.

Types of Structure

In the field a number of types of structure may be distinguished. To examine the structure, a quantity of soil should be lightly shaken or pulled apart. This is best done when the soil is moderately dry. Pressure should be avoided as this may alter or destroy the structure. The sides of a hole or trench do not show the natural structure, owing to deformation by the spade or pick used in digging.

Many soils show no definite structure. Coarse sands poor in colloidal matter have no power of aggregation into compound particles, but even soil containing colloidal matter may show poor aggregation. This is seen in the bleached horizon of podsols, which have a loose single-grain structure. Lack of structure is seen also in alkaline soils, in which the colloidal material has sodium as the dominant ion. Such soils are sticky when wet, and on drying out, form hard rock-like lumps.

Considering soil with definite structure, a number of types may be recognized. No agreed system exists, but for convenience, the structures commonly occurring may be grouped into (1) spheroidal; (2) cuboidal; (3) prismatic and columnar; and (4) platy.

In spheroidal structures the aggregates are roughly rounded. Soft and porous aggregates are called *crumbs.* This is the type of aggregate commonly found in fertile British soils. Where the aggregates are harder, and more compact, the structure is called *granular,* as in the black earths or tshernosems. Hard rounded granules are termed *buckshot,* a structure found in some American soils.

In cuboidal structures, the soil breaks up into roughly cuboidal or polyhedral aggregates with flattish faces and fairly well-defined edges. Large aggregates are called *clods,* medium aggregates, *lumps,* and small aggregates, *nuts,* the corresponding adjectives being cloddy, lumpy, and nutty. These structural types are commonly found in subsoils poor in organic matter, the larger aggregates being found in the lower horizons.

Columnar and prismatic structures may occur in certain clay subsoils. They are probably developed as a result of drying out and shrinkage. In some badly drained soils, a variant is found with roughly triangular pyramidal elements.

Finally, in some fine sandy surface horizons that are otherwise structureless, platy or laminar structures may be seen.

The structures above described are not always easy to recognize, particularly in moist soils. Often, they can only be discovered by allowing an exposed face of the soil in section to dry out and carefully picking at the surface in order that the structural elements may separate with a natural fracture.

Plasticity and Cohesion

Many of the difficulties of cultivating a clay soil are a consequence of their possessing the closely related properties of plasticity and cohesion. When a clay soil is wet it is plastic; when it is dry it is cohesive.

Whilst plasticity is a generally recognized property of such materials as wet clay, putty, pitch, etc., it is not a simple matter to give a concise definition of this property and to lay down a method for measuring it. Plasticity may be defined as the property possessed by certain substances of changing shape continuously under the influence of an applied force, and retaining the shape thus impressed after the force is removed. Thus if we take a lump of wet clay, we can mould it to any desired shape by applying a force to it, and this shape will be retained when the force is no longer exerted. This last condition distinguishes plasticity from fluidity and elasticity. A fluid will change shape continuously under an applied force, but also has the property of flowing. An elastic body will change shape continuously under the influence of an applied force, but when the force is removed, it will regain its original shape.

Plasticity is shown by clay soils only when certain proportions of water are present. If we take some dry clay and mix it with water to form a cream, the mixture behaves as a viscous fluid. As the proportion of clay to water is increased, i.e. as the moisture content is lowered, the paste becomes more viscous. It is easy to test whether it is still fluid by placing the paste in a round-bottomed porcelain dish and drawing a V-shaped furrow with a knife-blade. As long as the paste is liquid, the furrow will fill up, either naturally or after tapping the bottom of the dish smartly on the palm of the hand. A point is reached when the furrow does not fill up. The paste has now ceased to be fluid. It is now plastic for it can be moulded in the hand and will retain the form impressed on it. The point at which the clay-water paste just ceases to be fluid is known as the *upper plastic limit.*

If more dry clay is added to the paste, with thorough mixing, the plastic mass becomes stiffer. To test whether it is still plastic, it can be moulded into a cylindrical shape and rolled out between two flat pieces of wood. As the paste becomes drier, the cylinder may break on being rolled out, but the pieces can still be further rolled out. At length a point is reached, with further drying, at which the paste can no longer be rolled out but breaks into small pieces. This is the *lower plastic limit.* Samples of the paste are taken a the upper and the lower plastic limits and their moisture content determined by drying to constant weight in an oven. If it is found, for example, that the moisture content of a certain clay at the upper plastic limit is 50 per cent. and at the lower plastic limit 30 per cent., then it means that the soil is plastic over a range of moisture contents from 30 to 50 per cent. The *plasticity number*, which is a conventional index of plasticity, is the difference between the upper and the lower plastic limit, in this case, 20. The following typical figures were obtained by Atterberg, who first worked out the method.

Soil.	*Upper Limit.*	*Lower Limit.*	*Plasticity Number*
Silurian Clay . . .	67	40	27
Freshwater Clay . . .	52	37	15
Glacial Marl . . .	30	24	6

It should be remarked that the actual moisture content at either of the limits is not in itself an index of plasticity. It is rather the range over which plasticity is shown. Generally speaking, very plastic clays have plasticity numbers greater than 20, moderately plastic soils from 10 to 20, and feebly plastic soils less than 10. Many light soils are devoid of plasticity, i.e. when they are at their fluid limit, they do not show plasticity.

It should be observed, in criticism of this method, that what is measured is not plasticity itself, but the range of moisture content over which the property is shown. It is thus only an indirect method, and plasticity as a property remains unmeasured.

The lower limit of plasticity marks the upper limit at which the clay, in an arable soil, can be worked. Thus, if a soil has a lower plastic limit of 30 per cent. moisture, then if it is worked at moisture contents above this it simply " pastes." This may not be a serious disadvantage in the lower part of the plastic range if the object is simply to turn the land over for the winter. It is quite out of the question in spring, when the object of cultivation is to obtain a seed-bed. The clayland farmer knows by long experience when the soil is fit to work, or, in other words, below the lower limit of plasticity, in which condition all operations of cultivation tend to break it down.

Cohesion in soils is the force that resists the breaking of the soil by tillage implements. When a soil is ploughed a considerable proportion of the work done by the plough consists in severing the furrow away from the body of undisturbed soil. Work is also required to overcome friction and to lift and invert the furrow. Cohesion must be overcome also in breaking down clods in the operations of harrowing and rolling to produce a seed-bed.

There are two different kinds of cohesion in soils. In the first place, there is the cohesion due to the surface tension of water films. This is the kind of cohesion shown by moist sand. On drying, surface tension ceases to operate and the sand grains fall apart. The other kind of cohesion is true cohesion and depends on the presence of colloidal material in the soil. It is, in fact, due to the adhesive property of soil colloids. Unlike the first type of cohesion, true cohesion is at minimum when the soil is wet and increases as the soil dries out.

No completely satisfactory method has been devised for measuring soil cohesion. The best known method is based on the work of Atterberg, who measured the force required to cause a steel wedge to break a specially prepared block of soil. There are many difficulties inherent in the method, one of the chief being the lack of uniformity of the soil itself. This can be overcome to some extent by averaging a large number of determinations. Another objection is that when the block is moist it does not break sharply but undergoes an initial deformation.

In spite of the difficulties of measuring cohesion the general facts are reasonably clear. Cohesion increases with decrease in moisture content and is greater in heavy clay soils than in lighter soils. Soils showing high plasticity generally show high cohesion. With very heavy soils, the cohesion may be so great even when the soil is not completely dry that tillage operations become exceedingly difficult. It is well known that some soils when dry can only be ploughed by means of tractors. The same soils are also very difficult to work down to a seed-bed by rolling and harrowing if they become too dry. The clay farmer knows well that if his soil gets too dry he must wait for a shower of rain before he can work his land down. When the hard intractable clods are moistened, the soil colloids swell and the clods readily break down when worked. Herein lies the difficulty of working clay soils. If the soil is too wet, it becomes plastic and tillage operations have the effect of kneading it into a compact mass of clods, whilst if it is too dry, the cohesion is such as to resist the tillage operations meant to break it down. The farmer, therefore, needs great experience to know when to catch his soil in the right state. In a difficult season this is no easy matter, and he may have to be content with a rough seed-bed.

Both plasticity and cohesion can be mitigated by the presence of organic matter. Liberal dressings of farmyard manure improve the tillage properties of clay soils. The same effect is showm when clay soils are ploughed up after being many years in grass. Frost can be of great assistance. If a heavy clay soil is ploughed up at the beginning of the winter, the alternations of frost and thaw break it down, so that if it is caught at the right moisture content in the spring, it will readily work down to a seed-bed.

CHAPTER V

SOIL MOISTURE

Water required for the Growth of Crops—Retention of Water by Soils: Hygroscopic Moisture; Imbibitional Moisture; Capillary Moisture; Gravitational Moisture—Soil Moisture Constants: *p*F Value—Water-table—Movement of Water in Soils—Percolation, Evaporation, and Transpiration—Availability of Water to Plants—Seasonal Moisture-cycle—Effect of Drainage—Effect of Cultivations—Drying Effect of Crops—Bare Fallows—Dry Farming—Effect of Dung on Retention of Water by the Soil.

THE amount of water transpired by various plants during their growth has been investigated by Lawes and Gilbert at Rothamsted, by Hellriegel in Germany, by Wollny in Munich, and by King in America. The general principle upon which these observers have worked has been to grow the plants in pots and measure the amount of water consumed during growth, care being taken to eliminate or allow for losses by evaporation from the bare ground, and also to render the conditions of the plant's life as similar to those of the open field as possible. Finally, the plant is washed free of soil, dried, and weighed, so that a ratio is obtained between the dry matter produced and the water consumed during growth. Some of the numbers obtained are given in the following table: it will be seen that the same plant gives very different results with the different observers.

	Lawes and Gilbert.	Hellriegel.	Wollny.	King.
Wheat . . .	225	359	...	...
Barley . . .	262	310	393	774
Oats . . .	...	402	557	665
Red Clover . .	249	330	453	...
Peas . . .	235	292	477	447

The divergencies in these results are intelligible, if we consider that the "transpiration" process by which the water is lost, and the "assimilation" process by which the plant gets heavier, have no necessary connexion, though both become active under the same stimuli of light and warmth. Some leaves transpire rapidly as a means of maintaining a low temperature whilst absorbing large amounts of radiant energy from the sun; other plants that have to resist drought reduce the transpiration by a thickened cuticle, or by a more concentrated cell sap. Dr. H. Brown has shown that of the radiant energy falling upon a sunflower leaf on a bright August noonday, about 95 per cent. was consumed in evaporating the transpiration water; of the energy falling upon the same leaf in bright diffuse daylight, only 28 per cent. was used up in evaporation. Comparing in these two cases the water transpired with the carbohydrate produced (and this will be about $\frac{9}{10}$ of the total dry matter) we find in the sunlight the ratio was 347 to 1, in the diffuse daylight 234 to 1. Further investigations are desirable; but, taking the whole group of observations, we shall be justified in assuming that our ordinary field crops transpire about 300 lbs. of water for each lb. of dry matter produced. It now remains to translate this approximate figure into tons of water per acre required to grow the ordinary crops. The following table shows the weight at harvest of a fair yield of the crop in question, the percentage of water contained in the crop, the weight of dry matter produced per acre, then the water transpired as deduced from the dry matter produced, and, in the last column, this same amount of transpired water recalculated as inches of rain.

Crop.	Weight at Harvest.	Per cent. of Water.	Weight of Dry Matter at Harvest.	Calculated Water transpired during Growth.	
	Tons per acre.		Tons per acre.	Tons per acre.	Inches of Rain.
Wheat	2·5	18	2·05	615	6·09
Barley	2	17	1·66	498	4·93
Oats	2·5	16	2·10	630	6·24
Meadow Hay	1·5	16	1·26	378	3·74
Clover Hay	2·0	16	1·68	504	(?)
Swedes	17	88	2·04	612	6·06
Mangolds	30	88	3·60	1080	10·69
Potatoes	7·5	75	1·87	561	5·55
Beans	2	17	1·66	498	4·94

It will be seen that in all cases the amount of water transpired by the crop is a notable fraction of the total annual rainfall, particularly so in the case of a root crop like mangolds, which in the south and east of England will often require a full half of the total rain falling within the year. As some of the rainfall runs straight off the surface into the ditches, and another portion is lost to the land by percolation into the springs, as again a considerable fraction is evaporated at certain seasons from the bare surface of the soil, it is evident that the water supply, even in our humid climate, is far from sufficient for the maximum of production, and may easily fall below that required for an average crop. Indeed, we may take it as certain that the yield is more often limited by the water available than by lack of the other essentials of growth—light and heat, manure, etc. Of this we can have no better proof than the enormous crops grown by irrigation on sewage farms. Where the conditions are favourable, and the farm is situated on a free draining sandy or gravelly soil, so that the water can be often renewed and drained away to keep the soil supplied with air as well as water, the production of grass, cabbages, and other green crops is multiplied five or even tenfold by the unlimited supply of water. Speaking generally, over a great part of England, where the annual rainfall is from 25 to 35 inches, a large proportion of which falls in the non-growing seasons it is necessary to husband the water supply, and it will be found that one at least of the objects of many of our usual tillage operations is the conservation of the moisture in the ground for the service of the crop.

It is evident that for the satisfactory growth of crops an abundant supply of moisture is necessary. Indeed, shortage of moisture is perhaps the most common cause of unsatisfactory growth. But plant roots also require oxygen for respiration, and if there is an excess of moisture in the soil the supply of oxygen is necessarily restricted. In soils with defective drainage, root development is restricted to the upper part of the soil to which air has access. As factors in soil fertility, therefore, moisture supply and air supply are closely linked. Excess of moisture means deficiency of air ; excess of air means deficiency of moisture. In practice, most cases of infertility, or of low productiveness can be traced down to unsatisfactory moisture-air conditions in the soil.

From these considerations, it is evident that the study of the moisture relationships of soils is of the highest importance. We have to consider how soils retain moisture, how moisture moves about in the soil, and how the rain or irrigation water received by the soil is disposed of.

Retention of Water by Soils

The problem of the retention of water by the soil may be reduced to its simplest terms by considering the behaviour of water in an " ideal " soil, by which is meant not the best possible soil for the growth of crops, but an imaginary soil consisting of uniform spheres in close packing. The spaces between will form a cellular system consisting of cells communicating with each other by relatively fine necks or channels. At low moisture contents the moisture will be distributed in thin rings round the points at which the spheres touch. This is shown in Fig. 6A. For simplicity of exposition the arrangement is shown in only two dimensions. When more moisture is present the rings join up as in Fig. 6B. The essential

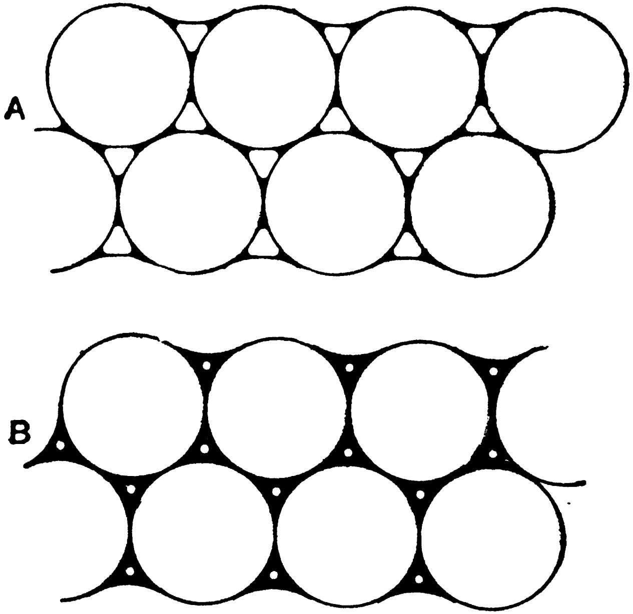


Fig. 6.—Distribution of Moisture in an Ideal Soil.

feature is that at moisture contents above that represented by the first phase all the water present is in capillary connexion. The interstitial spaces behave as if they are a series of channels of varying cross-section. This has important consequences for the distribution of water in such a system. Consider a tube of varying cross-section as in Fig. 7. If the lower end stands in water, the water in the tube will stand at a certain height, namely $2T/r$, where T is the surface tension, and r is the inner radius of the tube. If the water in the outer vessel is now raised there will be a corresponding rise within the tube until the construction is reached when the height will rise suddenly to $2T/r'$, where r' is the radius of the narrower portion of the tube. A similar discontinuous fall will occur if the outside level is lowered so that the level inside the tube passes from a narrower to a wider capillary. It is obvious from these considerations that in the more complicated capillary system of the soil a different moisture distribution will be attained according to whether water rises from below or is added from above.

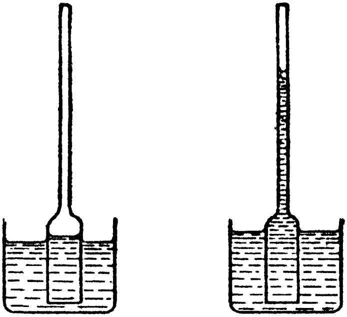


Fig. 7.—Effect of Change in Internal Diameter on Height of Capillary Rise in a Tube of Varying Cross-section.

The ideal soil is, of course, an abstraction, and the study of moisture relationships in such a soil is of value only because of the light it throws on the moisture conditions in actual soils. The nearest approach to such a soil is a coarse sand low in organic matter and clay. Most of the soils with which we have to deal in practice contain appreciable amounts of clay and organic matter present as the clay-humus complex, or soil colloid. It is this colloidal material that plays the most important part in the retention of moisture by ordinary soils. On being moistened, it absorbs water and swells in the same way as a piece of gelatine placed in water. Water thus held is termed *imbibitional moisture*, and in ordinary soils under ordinary field conditions, most of the moisture is present in this form.

The retention of water by soil can be conveniently explained by considering the changes in moisture status that take place, starting from an air-dry soil and increasing the moisture content until the soil is completely saturated.

Hygroscopic Moisture.—When a soil is dried in air at ordinary temperature it still retains a certain amount of moisture, which is termed *hygroscopic moisture.* The actual amount thus retained will depend on the humidity of the atmosphere, and on the character of the soil itself. A flat dish with a thin layer of soil exposed in the laboratory will vary in weight from day to day. On a damp muggy day its weight will increase; in hot, dry weather, on the other hand, it will decrease in weight. In order to determine the *hygroscopic capacity* of a soil it must be brought to equilibrium with an atmosphere of a standard humidity. There are several conventional methods for carrying out this determination. The maximum hygroscopic capacity is the amount of moisture a soil can hold when in equilibrium with a saturated atmosphere. It is more usual to determine the moisture held in equilibrium with an atmosphere maintained at a standard humidity, e.g. 50 per cent.

If the hygroscopic moisture content of different soils is compared under standard conditions it is found that it depends on the proportions of colloidal matter present. Hydrated ferric oxide also has a marked effect on the hygroscopicity of soils. The following figures from Mitscherlich illustrate the effect of different soil constituents on hygroscopicity :

Material.	Hygroscopic Moisture per cent.
Quartz sand	0·03
Loamy sand	1·0
Sandy loam	2·4
Medium loam	3·0
Heavy loam	6·5
Peat	18·4
Ferruginous clay	23·8

Hygroscopic moisture is unavailable to plants and is held as thin films of approximately molecular dimensions on the surfaces of mineral particles and as water of constitution of the soil colloids.

Imbibitional Moisture.—When water is added to air-dry soil, the colloids begin to absorb water of imbibition, swelling in the process. The soil now becomes visibly moist, as shown by its darkening in colour. It also begins to show cohesion and, eventually, adhesion to external objects. During this stage of moistening the soil colloids are absorbing moisture, the process being analogous to that taking place when a piece of gelatine is placed in water. The soil colloids, like gelatine, swell on being moistened. This can be shown by putting dry soil in a shallow dish and levelling it with the edge. When the soil is allowed to absorb water, it will be seen to swell up over the edge of the dish, the amount of swelling depending on the amount of colloidal material present. Most of the water held by imbibition is available to plants, but is tenaciously held against mechanical forces.

Capillary Moisture.—With increasing moisture content water begins to appear as external films on the surfaces of the soil particles and crumbs. At first these films occur at the points of contact of particles and crumbs, the so-called *pendular stage*, succeeded with increase in moisture by the *funicular stage* in which the films become continuous. The behaviour of this film water is analogous to that postulated for the water in an ideal soil.

Water in external films is capable of movement by capillary action. Thus, if a section of moisture is bounded at one end by a highly curved surface, and at the other end by a less curved surface, water will tend to move towards the region of greatest curvature. Over the lower part of this range when only the finer capillaries are filled with water, movements are very slow, so that although capillary action is theoretically possible it may be practically insignificant.

Gravitational Moisture.—As the amount of moisture in the soil increases still further, the larger interstices become filled with water. Such water is subject to gravity, and can drain away to lower levels in the soil. Finally the pore space becomes completely filled to the exclusion of air and the soil is then saturated, or, in ordinary speech, waterlogged.

We have noted a number of stages as the moisture status of the soil is increased. These are not hard and fast limits, but should be regarded as points in a continuous series. Thus the hygroscopic capacity of the soil is greater in equilibrium with a saturated atmosphere at a higher than at a lower temperature. It is theoretically possible therefore, for an air-dry soil to become moist with fall in temperature. Indeed the dew deposited on the soil on fine clear nights mainly originates from the soil itself. Changes in temperature may also result in moisture passing from the capillary to the gravitational category.

Soil Moisture Constants

From the beginning of the study of soil moisture much attention has been given to methods for expressing the moisture capacity and moisture status of soils. One of the earliest methods, designed to measure the *maximum moisture capacity* of soils, consisted in placing soil in a shallow cylinder with a perforated bottom, saturating it with water, and allowing the excess to drain away. The figure obtained represents the amount of water retained by the soil in the vicinity of a free water surface. In practice, the results, if expressed on a volume basis, approximate to the pore space, because under such conditions only the larger interstices are void of water.

If we consider a long column of soil with its lower end in water the proportion of voids will increase with height until, above a certain level, only the finer capillaries will be full of water. A method designed to measure the capacity of a soil to retain water in its finer capillaries is to determine its *moisture equivalent.* Soil is placed in cups with perforated bottoms fitted to a centrifuge whereby they can be submitted to a centrifugal force 1,000–2,000 times that of gravity. Water in the larger interstices is thrown out and the moisture retained is the imbibitional moisture associated with the soil colloids, together with water in the smaller interstices and thin external films. The method is not wholly satisfactory, because by increasing the speed of rotation, thereby increasing the centrifugal force, still more water can be thrown out. Lebedev considers that a limit is reached at a centrifugal force of 18,000 g. The amount of moisture retained against this force is termed the *maximum molecular water capacity.*

Another measure of moisture capacity is the *sticky point,* which is the percentage of moisture in the soil at which a paste of soil and water can be worked without its adhering to external objects. In this determination the soil is, of course, in the puddled or deflocculated state. This constant represents the point at which the soil colloids are saturated with imbibitional moisture. Interstitial water is also present and amounts to approximately 16 per cent. by weight. The sticky point moisture, therefore, less 16 per cent., should give an approximate measure of the imbibitional moisture capacity.

*p*F *Value*

A distinction must be drawn between the actual percentage of water in the soil, and its wetness. Two soils may contain the same percentage of moisture, but may differ in the availability of this moisture to plants. For example, let us compare a sandy soil and a heavy clay each containing 10 per cent. of moisture. The sandy soil will be visibly moist and have perhaps 5 per cent. of moisture available for plants, whilst the clay soil will be barely moist and have no moisture available for the use of plants.

To bring the moisture status of soils to a common basis of comparison the idea of *capillary potential* was introduced. To explain this, let us consider a quantity of moist soil in a shallow cylinder with a porous bottom. A Buchner funnel with a hardened filter paper fixed to the bottom would serve. When the pressure is the same above and below the filter the moisture retained by the soil will be that represented by its maximum moisture capacity. If the funnel is fitted to a filter flask and the pressure in the flask reduced there will be a certain pressure difference or suction across the layer of moist soil, and water will move out of the larger interstices to pass through the filter into the flask. As the pressure falls in the flask more water will be drawn out of the soil. When the pressure in the flask falls to vacuum the pressure difference is one atmosphere. This pressure difference corresponds with a water column of about 1,000 cm. in height. The height of the water column corresponding with the pressure difference is a measure of the capillary potential. Schofield has introduced a simple measure termed *p*F, which is the logarithm of the capillary potential, in this case 3·0. In the abovementioned experiment, if the pressure difference were 0·1 atmosphere equivalent to 100 cm. of water the *p*F of the soil at equilibrium would be 2·0; with a difference of 10 atmospheres the *p*F would be 4·0.

Soils at the same *p*F are in moisture equilibrium. Moisture will tend to move from soil at low *p*F to soil at a higher *p*F. The following are certain soil moisture constants translated into terms of *p*F:

	*p*F
Hygroscopic moisture (50 per cent. humidity)	6·0
Moisture at wilting point	4·2
Moisture equivalent	3·0

Water-table

If a deep hole be dug in a soil in the lower slopes of a valley a level is reached at which the soil is completely saturated, so that water stands in the hole. This level of complete saturation is known as the *water-table*, or *ground-water level.* It follows the general contours of the land, but approaches the surface more closely at the bottoms of valleys than in the uplands. In very wet marshy land it is practically at the surface. The level fluctuates, being highest in winter and lowest in summer. Water falling on the soil in excess of that used by plants or evaporated from the surface ultimately finds its way down through the soil to the *ground-water.* An impervious layer, by holding up percolation may give rise to a *perched water-table,* i.e. a water-table at a higher level than the regional water-table, whose position is governed by the lie of the country.

Where a water-table lies far below the surface it can have little effect on moisture conditions at the surface, but where it lies near the surface, it dominates the moisture relationships of the soil. A column of soil in equilibrium with a water-table will have a decreasing moisture content with height. Immediately above the water-table all but the largest interstices will be full of water. With increasing height the water is confined to smaller interstices and the moisture content decreases, until at a few feet above the water-table only the finer interstices of the soil colloidal material are filled with water and the moisture content approaches that indicated by the imbibitional moisture capacity.

Movement of Water in Soils

Water may move in soils (1) by gravity ; (2) by capillary action ; and (3) by vapour transfer.

Water in the larger interstices of the soil is free to move under the influence of gravity, and drains away to the ground-water. Of course, if the water-table is near the surface the larger interstices remain filled. Drainage consists essentially in lowering the water-table in order that excess water can drain away by gravity.

The permeability of a soil to water movements depends largely on its structure. Two soils may have the same percentage pore space, but whereas the one readily allows water to drain away, the other is highly impervious to water movements. A useful distinction has been drawn between capillary and non-capillary porosity. The non-capillary spaces are those between the structural elements and layer particles of the soil, whilst most of the capillary spaces are those within the soil crumbs. Water and air can move freely through the former, but scarcely at all through the latter. The more the soil is aggregated into compound particles or crumbs, the greater will be the proportion of non-capillary pore space. It is probable that the permeability of the soil may be affected also by the presence of interstitial spaces that resist wetting. When a soil is saturated, a certain amount of air remains trapped in spaces within the soil. The space occupied by these restricts the amount of non-capillary pore space available for water movements.

Capillary movement takes place from wet soil to drier soil, i.e. from regions of low *p*F to regions of high *p*F. Theoretically, water should distribute itself in a body of soil until the *p*F becomes uniform, but in practice this movement only takes place to a limited extent, because water movements in the finer pores and capillaries is so slow owing to friction as to be negligible.

Capillary movement of moisture can take place against gravity, the process being analogous to the rise of oil in a lamp wick. This capillary rise can only operate to a limited extent. Keen at Rothamsted took a number of 6-foot cylinders sunk in the soil and saturated them with water to the surface. He allowed them to dry out and found that even with a heavy loam the ground-water level did not sink below 80 cm., from which he concluded that capillary rise could not operate over more than this distance. The corresponding figure for a fine sand was 70 cm., and for a coarse sand 35 cm. These findings are contrary to earlier views, according to which plant roots could obtain moisture by capillary rise from great depths in the soil. It means that unless a water-table is within 2 or 3 feet of the depth to which roots penetrate, it cannot contribute to their moisture requirements, which must be met by the supplies of moisture in the soil within their root range.

We may now consider the distribution of water added to a dry soil from above by rainfall or irrigation Starting with dry soil, if we add, say, one inch of rain by irrigation the immediate surface layer will be completely saturated. The excess water in the larger interstices will at once sink to lower levels, leaving the finer interstices and capillaries full of moisture, and itself entering the finer interstices at lower levels. There will then be a slow transfer by capillary movement from the surface to the layers immediately below. This transfer will take place only to a limited extent and an equilibrium will be reached with a certain depth, perhaps a few inches, saturated up to what is known as *field capacity.* If the soil is then examined in profile it will be seen that there is a sharp transition from moistened to dry soil. This is, of course, in line with practical experience that even heavy rain falling on dry soil only moistens the soil to a very limited depth. It can be illustrated in the laboratory by allowing a drop of water to fall on a dry filter paper, when the moisture will spread to a sharply defined circular patch.

The third way in which moisture can move within the soil, namely by vapour transfer, is not so clearly understood. It depends on the existence of a temperature gradient in the profile. During the winter months the deep layers of the soil are at a higher temperature than the surface and if the profile is sufficiently well drained, distillation will take place from the subsoil to the surface. In the summer, when the surface is warmer than the subsoil the distillation will be in a downward direction. Such movements can only take place if there is freedom of vapour movement. They cannot occur in waterlogged soils. Their magnitude has not been determined, but it is possible that they are in part responsible for maintaining the wetness of the surface soil in winter and its dryness in summer. On the other hand, some workers have doubted the possibility of this type of transfer being appreciable.

Percolation, Evaporation, and Transpiration

Rain falling on the soil is disposed of in four ways, namely by (1) evaporation from the surface of the soil; (2) transpiration by crops growing on the soil; (3) surface run-off; and (4) percolation to lower levels and eventually into the drainage. Under ordinary British conditions, run-off from the surface is negligible and the whole of the rainfall is accounted for by evaporation and transpiration into the air and percolation into the drainage. The greater the losses from the soil by evaporation and transpiration, the less will be the percolation into the drainage. Thus, in the absence of run-off, percolation represents the difference between rainfall and evaporation.

Whilst the flow of water from a field-drain may be taken as a rough measure of the amount of percolation going on at any given time for that soil, the movement may be followed more closely by means of a lysimeter or drain-gauge. As a rule, the records of these instruments are vitiated by the disturbances undergone by the soil in filling them; but the drain-gauges at Rothamsted were constructed by building cemented walls round blocks of earth *in situ*, and then gradually introducing a perforated iron plate below to carry the soil. Fig. 8 shows the mean monthly records of rainfall and percolation through a depth of 20 inches and 60 inches respectively, over a period of thirty-five years.

It will be seen that of the total rainfall a little less than one-half percolates through 60 inches of the Rothamsted soil; it should be remembered, however, that the surface of these gauges is kept free from weed or any growth. The total drainage through 20 inches of soil is practically the same as that through 60 inches, but rather a greater proportion of the rainfall comes through the 60-inch gauge in the winter and through the 20-inch gauge in the summer. In the winter months the percolation reaches as much as 80 per cent. of the rainfall; in August little more than 20 per cent. of the rainfall finds its way through the layer of soil. When the ground has become dried to any depth in the summer, percolation may be much hindered by the air within the soil and the want of a continuous film of wetted surfaces to lead the water down by surface tension. The top layer of soil becomes thoroughly wetted and will not allow the air below to escape ; only after some time are local displacements of the air set up, which enable the water above to make connexion with the wetted subsoil below, so that percolation can begin. For this reason summer rains falling in a season of drought are often noticed to be of little benefit to the crop, because they are retained near the surface until wholly evaporated, instead of increasing the stock of moisture at the lower levels where the roots of the plant are then operative in obtaining water.

Percolation is distinguished from " flow " by the fact that the water is supposed to have free surfaces, so that surface tension comes into play. It takes place under the action of gravity through the pore space proper, and also through the cracks, the worm tracks, the passages left by decayed roots, and other adventitious openings in the soil. The percolation proceeds until the zone is reached where the pore space is completely filled ; this is the " water-table," and is the level at which water stands in the wells. Above the water-table the moisture content will show a gradual decrease with height ; though most probably there will be an irregular distribution, with zones which contain an excess of water travelling downwards with greater or less rapidity, according to the texture of the soil. It is these temporarily saturated zones which cause the ordinary tile drains to run, although situated many feet above the permanent water-table. A soil in which percolation has ceased, though it may still contain much water, will not part with it to a drain ; the water cannot break away from the elastic film and run off down the drain, unless it be present in such an excess that the surface tension is insufficient to hold it against gravity. But in a clay soil, percolation is so slow that the upper few feet of soil may become saturated by the winter rains and remain so for months, if percolation has to proceed all the way down to the water-table ; by the introduction of drains, the percolating column is shortened to the distance between the surface and

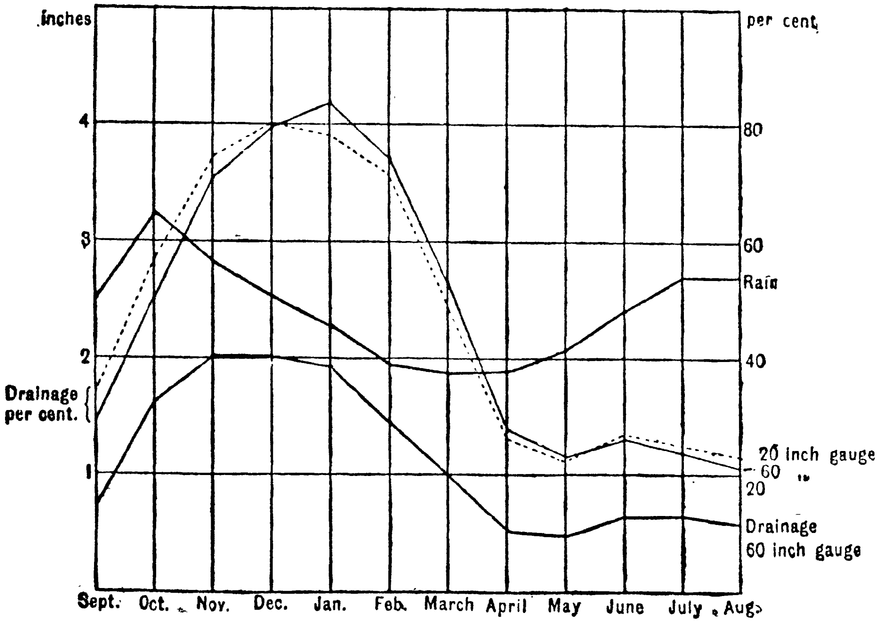


FIG. 8.—Diagram showing Rainfall and Percolation at Rothamsted, 1870–1905.

The two heavy curves show rainfall and percolation through the 60″ gauge in inches; the dotted and the lighter continuous curves show the percolation through the 20″ and 60″ gauges as percentages of the rainfall.

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the drain. In a coarse-grained sandy soil percolation is very rapid, the land dries quickly after rain, and retains a minimum of water by surface tension ; in fine-grained soils, which are, however, not too fine for percolation, the excess of rain will be removed rapidly enough to keep the soil below the saturated condition, yet enough water may be retained to supply the needs of the crop between the intervals of rain.

The difference between rainfall and percolation represents loss by evaporation and transpiration. Water is continually being lost from the surface of bare soil and to a decreasing degree from lower layers of the soil. The Rothamsted data shown diagrammatically in Fig. 8 indicate the effect of temperature on evaporation. The daily rate of loss varies from about 0·012 in. in January to about 0·067 in. in July and August. From these figures, it can be readily understood that very high rates of evaporation obtain in hot climates, and that during the hotter part of the year, even in temperate climates such as our own, the evaporation exceeds the rainfall, so that the soil is only moistened to a limited depth, without any appreciable yield of drainage. The greater rates of drainage during the winter months in our own country are due as much to the diminished evaporation as to the actual magnitude of the rainfall.

Apart from the effect of temperature on evaporation, atmospheric humidity is an important factor, the rate of evaporation being greater with a dry than with a moist atmosphere. The losses by evaporation with a dry atmosphere are further increased when there is wind. Thus the dry winds of March, even although the temperature is low, have an intense drying action on the soil.

Losses of moisture from the soil are increased when the soil is covered by a growing crop. For example, it has been found in Australia that under lucerne the water-table was considerably lower than that under bare soil, even although extra water was added by irrigation. In certain pasture improvement experiments in Wales, it was found that the replacement of a poor by a better sward resulted in an appreciable reduction of wetness. On the other hand, it has been shown that the felling of forest often results in temporary wetness in the soil. This disappears when new plantings are established.

Availability of Soil Moisture to Plants

Even in a moist soil, a certain proportion of the moisture present is unavailable to plants. The drier the soil the more firmly is its moisture held. This may be illustrated by the behaviour of a wet sponge. When saturated, water can easily be squeezed out. As the sponge becomes drier more pressure is needed to squeeze water from it, and the last traces of water are so firmly held that no amount of pressure can remove them. So, when the soil becomes drier it retains moisture more firmly against absorption by plant roots, until a point is reached when the roots cannot obtain water at a rate sufficient to make good losses by transpiration. The plant then looses its turgor or, in ordinary parlance, wilts. Briggs and Shantz grew a number of plants in water-tight containers and allowed them to use up the soil moisture until a point was reached when they wilted permanently, i.e. failed to recover even when placed in a saturated atmosphere. The moisture content of the soil at this point is termed the *wilting coefficient.* Naturally, this would differ somewhat for different plants, but for most ordinary plants the wilting coefficient is approximately one and a half times the hygroscopic coefficient.

Only the water in the soil in excess of the amount indicated by the wilting coefficient is available for the crop. Sachs was the first to show by experiments in pots that tobacco plants will begin to wilt before the soil has parted with all its moisture. When wilting began with a sandy soil the sand in the pot still contained 1·5 per cent. of water, with a clay soil 8 per cent. of water ; with a mixture of sand and humus there was as much as 12·3 per cent. of water retained by the soil. Heinrich has also shown that wilting begins before the water content of the soil has been reduced to the hygroscopic water limit, as the following figures demonstrate :

	WATER PER 100 OF DRY SOIL.	
	When Plants Wilt.	Hygroscopic Water.
Coarse Sand . . .	1·5	1·15
Sandy Garden Soil . .	4·6	3
Fine Sand, with Humus .	6·2	3·98
Sandy Loam . . .	7·8	5·74
Chalky Loam . . .	9·8	5·2
Peat	49·7	42·3

King has made some observations of the amount of water still present in soils in the field which had become so dry that growth was at a standstill and the plants were wilting.

Depth.	Nature of Soil.	Per cent. of Water under Clover.	Under Maize.
0″ to 6″	Clay Loam	8·4	7
6″ „ 12″	„	8·5	7·8
12″ „ 18″	Reddish Clay	12·4	11·6
18″ „ 24″	„	13·3	12
24″ „ 30″	Sandy Clay	13·5	10·8
40″ „ 43″	Sand	9·5	4·2

Under these conditions all the soils were about equally dry, so far as any ability to part with their water went ; if the estimates made previously of the area of surface of the particles constituting various kinds of soil be combined with these percentages to calculate the thickness of film of the water on that surface, it will be found that on all soils the film possesses approximately the same thickness, about 0·00003 inch.

Because of the quantity of water which some soils will retain rather than give up to the plant, it is possible that such soils may have less available water for the plant than a much coarser grained soil which starts with a lower initial amount of water. For example, the clay and sand in the table above contain, when saturated about 26 per cent, and 18 per cent. of water respectively ; as the crop can reduce this to 12 per cent. in one case, and 4·2 per cent. in the other, both sand and clay yield about the same amount of water to the crop.

A good example of the fact that only the water in the soil that is in excess of the moisture held at the wilting point is available for the crop, is seen in F. J. Alway's studies of soil moisture conditions in the "Great Plains" region of North-Western America. There the rainfall is only from 12 to 15 inches annually, and falls chiefly during the summer months; because of its insufficiency for the production of continuous crops, it is customary to take a bare fallow one season in three in order to accumulate the rainfall for the benefit of the two succeeding grain crops.

The table shows the water content of the soil down to the depth of 6 feet on two fields near Indian Head, Saskatchewan, taken at the end of July 1904, field B having been fallowed, and C having carried a crop of oats which had shown the effects of drought. Figures are given for the total water in the soil as sampled, the hygroscopic moisture as determined in the laboratory, and the difference, which Alway termed the free water:

Foot Section.	B, After Fallow. Water.			C, After Oats. Water.		
	Total.	Hygroscopic.	Free.	Total.	Hygroscopic.	Free.
First . . .	29·4	12·0	17·4	20·0	12·7	7·3
Second . .	14·9	3·9	11·0	22·4	13·2	9·2
Third . .	16·4	4·7	11·7	21·6	13·5	8·1
Fourth . .	17·4	5·5	11·9	16·1	4·6	11·5
Fifth . . .	21·8	7·6	14·2	15·1	4·2	10·9
Sixth . . .	19·6	8·0	11·6	15·9	5·9	10·0
Mean . .	19·9	...	12·9	18·5	...	9·5

In each field the upper layer of soil possesses a higher capacity for retaining hygroscopic moisture than does the lower layer, but in field C this upper layer is thicker than in field B. It will be seen from the table that as regards total water there is no great difference between the two fields, but when the hygroscopic moisture is deducted, B contains 3.4 per cent. more water available for the plant. This difference was manifested in the following season in the yield, which was only 2,160 lbs. of grain and straw on C and 9,200 lbs. on B. Had the really free water been determined, that which is in excess of the amount held by the soil when wilting sets in, these differences would have been even more pronounced, as is evident from the fact that the moisture in the soil at the wilting point is greater than the hygroscopic moisture but is in proportion to it.

Though the hygroscopic moisture gathered by the surface soil in the cooler and damper periods of the night cannot be passed on to the subsoil and given up to the roots, yet by its evaporation the next day it may help to keep the temperature of the soil down, and so indirectly diminish the loss of water to the soil. Of course, in certain conditions of air and soil temperature there is condensation upon the soil of visible water that can be available to the crops ; for example, in some months, drain-gauges yield more water than the rainfall, though a certain amount of loss by evaporation must also have taken place. This usually happens in the early spring, and can be set down to the condensation of dews by the thoroughly chilled ground from a warm and moist atmosphere.

The Seasonal Moisture-Cycle

We are now in a position to follow the changes in the moisture-status of a typical soil under British conditions throughout the course of the year.

Let us suppose that we are dealing with a well-drained soil having a deep water-table at, say, about 6 to 8 feet below the surface. At the end of a normal winter the whole profile will be thoroughly moistened, and there will probably be a certain excess of moisture capable of draining down to the water-table, which at this time will be at its highest level, possibly 6 feet below the surface. If no more rain falls, and if no evaporation takes place, the excess moisture will drain down to the water-table, and we shall get an equilibrium distribution, which may be represented by curve $XwYw$ in

Fig. 9. The moisture content at each depth represents the field capacity of the soil, except that in the vicinity of the water-table the moisture content will increase to the maximum water-holding capacity. The diagram has been simplified somewhat for the purpose of representation. Actually the field capacity of the surface soil would generally be greater than that of the immediate sub-soil, because of its higher content of organic matter.

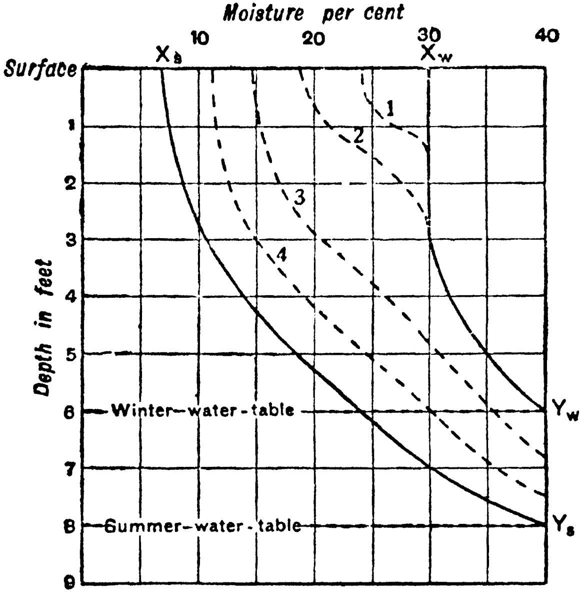

Fig. 9.—Changes in Moisture Profile during Spring and Summer.

In the spring, with warmer and drier weather, the soil will now begin to dry out, beginning at the surface. The process will be arrested by showers and even reversed by heavy rain, but in a normal season the profile gradually dries out and the demands of growing crops further increase the removal of moisture. The successive stages are shown by curves 1, 2, 3, 4 in Fig. 9, ending with the curve *XsYs*, representing the extremity of drying-out. The degree of drying-out will depend on the weather during the season, but even after the driest season, the soil will always be moist in the vicinity of the water-table, which will gradually fall, to reach its lowest level at the end of the summer. In a wet summer, the drying out and the fall of the water-table will be less pronounced. Showers falling during an ordinary summer moisten the soil to a limited depth and owing to the high temperature and the demands of crops, the added moisture is soon lost.

In the autumn, with lower temperatures and decreased evaporation, the rainfall becomes more effective. The successive stages after the first period of heavy rain might be represented by the curves in Fig. 10. Immediately after the rain has fallen the surface will be more than saturated. The

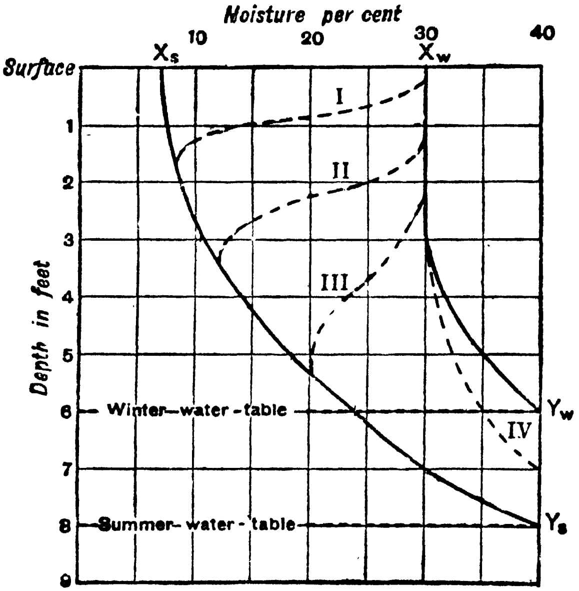

Fig. 10.—Changes in Moisture Profile during Autumn and Winter.

excess will then penetrate to lower levels until a limited depth, depending on the amount of rain that has fallen, is moistened up to field capacity. Successive rains further increase the depth of soil moistened to field capacity, until the winter moisture profile is again established. The stages are shown by curves I, II, III, IV in the diagram.

There are naturally many variations of the cycle as above outlined, depending on the character of the soil and the position of the water-table.

In a soil with a high regional water-table, the principal changes are those consequent on the seasonal fluctuations of the ground-water level. Where the water-table owes its position to the presence of an impervious stratum, however, the course of events is different. During the winter months the soil will be waterlogged from the surface down to the impervious layer, below which the underlying material may be quite dry. This was well illustrated by a bomb-crater seen in a field in Staffordshire. The field as a whole showed every sign of poor drainage, with water near the surface. In the bottom of the crater, however, was almost dry fissured clay. The wetness was due to an impervious stratum a few feet below the surface.

The Effect of Drainage

Drainage is usually regarded as a means of freeing the land from an excess of water, but it also has an important effect in rendering a higher proportion of the annual rainfall available for the crop, so that drained land will suffer less from drought than the same land in an undrained condition.

Land may require drainage for various reasons : it may possess a naturally pervious subsoil, and yet be waterlogged owing to its situation, or the subsoil may be so close in texture that percolation is reduced to a minimum and the surface soil remains for long periods almost saturated with water, especially if the slope is gentle and water lies after rain until very large amounts soak in. The flat meadows adjoining a river are often waterlogged because their surface is little higher than the water in the river and the general water-table in the adjoining soil. In these cases tile drains are of no value because of the want of fall ; open cuts and ditches draw off the water best, and by exposing some of the subsoil water both to aeration and evaporation, lead to the improvement of the land. Another cause of swampy water-logged land is the rising to the surface of a spring or a line of soakage, such as is always formed at the junction of a clay or other stiff soil with an overlying pervious formation, " when the sand feeds the clay," as the old rhyme runs. Such wet spots can be drained by tiles or by an open ditch cutting the springs or the line of soakage. Land lying on an impervious subsoil at the foot of a slope is often very wet because the water that has accumulated in the hill and soaked downwards is forced to the surface by the hydraulic pressure of the water above ; such seepage water rising to the surface from the subsoil is characteristic of many valley soils, and can best be dealt with by a system of tile drains. But tile drains are most generally employed and are of greatest value in dealing with stiff impervious subsoils, which cannot get rid of the rain falling upon them ; indeed, one of the prime improvements effected in English agriculture was the drainage of something like 3,000,000 acres of heavy land between the years 1840–70. A great portion of the work was unfortunately of little avail, because at first there was a tendency to set the drains too deep, at 4 feet instead of the 2 to 3 feet which have been found to answer best. With the increased cost of labour, tile draining has latterly become too expensive to be generally applicable. On really stiff soils, the true clays, it can, however, be cheaply replaced by mole drainage, a process by which a steel " mole," a pointed cylindrical bolt 2½ to 3½ inches in diameter, is drawn through the ground by a tractor or steam tackle at a depth of 18 inches to 3 feet. A preliminary examination of the land should be made to see where the clay begins. The mole hole should be 3 inches below this point. In strong soils the mole hole is reasonably permanent and does not fall in for several years. The gathering drains are made by the mole plough more closely together (as close as 9 feet) than is usual with tile drains, but the main drain into which they lead must be tiled or be an open cut or ditch with a few tiles to preserve each outfall of the moles. Mole drainage has proved to be a cheap and efficient method of unwatering clay land, and close shallow drains are more effective than those deeper and more widely spaced.

The effect of drainage is to lower the permanent water-table to the depth at which the drains are laid, so that instead of constantly stagnant water a movement of both water and air is established in the soil above the drain. In the first place, the introduction of the air which follows the water drawn off by the drains brings the whole depth of soil into activity, whereas previously only the portion not water-logged was available. Plant roots cannot grow without oxygen from the air, hence in a waterlogged soil the roots are confined to the surface layer only ; after drainage the roots can penetrate as far as the air extends. At the same time, all the fundamental chemical and biological processes of the soil, such as nitrification and weathering, are brought into action by the introduction of the oxygen upon which they depend. Later it will be seen that waterlogging results in the loss of nitrogen from the land when such manures as nitrate of soda are applied to it. It is the extended root range of the crop resulting from the introduction of air by drainage which enables the drained land to resist a drought better than before. In an undrained soil the roots are confined to a shallow layer, which they soon deprive of all moisture ; further supplies of water from the saturated soil move upwards very slowly in a clay soil, so that the plant may suffer greatly. In a drained soil, on the contrary, the roots traverse the whole 3 feet or so into which air has been admitted ; this mass of soil, even after it has given up by percolation all the water it can, will still hold much more than is contained in the shallow layer traversed by roots before drainage. Following upon drainage, a slow improvement in the texture of clay soil is always manifest : by the drawing of air into the soil, by the consequent evaporation and drying, a certain amount of shrinkage and a clotting of the fine clay particles result, which is never entirely undone when they are wetted again. Roots, which afterwards decay and leave holes, and deep worm tracks, are all brought into the soil by its aeration, and result in more rapid percolation. Again, the washing through the soil of soluble salts derived from the surface, especially the bicarbonate of lime which is so characteristic a constituent of drainage water, also induces flocculation of the fine clay particles. Lastly, there is a steady removal by the drains of the finest clay stuff, for whenever tile drains are running freely the water will be found slightly turbid with clay matter. All these causes contribute to establish a better texture in the drained soil, beginning at the tiles and spreading slowly outwards. The other result of drainage which may be noted here is the greatly increased warmth and earliness of a drained soil ; the high specific heat of water, and the cooling produced by evaporation when the water-table is near the surface, combine to hinder a waterlogged soil from warming up under the sun's heat in the spring, so that undrained land is notoriously cold and late.

Effect of Cultivation upon the Water Content of the Soil

In regions where the annual rainfall is not very high and occurs chiefly during the early winter months, it is important to get as much of it as possible into the soil for the use of the subsequent crop. Breaking up the stubbles after harvest is an important factor in catching the winter rain ; all land which is to lie through the winter, previous to the sowing of roots or spring corn, should be early turned over with the plough and left rough through the rainy season. On the old stubble which has been made solid by the weather and the trampling during harvest, the rain lies for some time and evaporates, and if the land be at all on a slope the water shoots off into the ditches. But the broken surface of a ploughed field both hinders the flow of the water and affords it many openings by which to sink in ; at the same time the increase of pore space in the loose ploughed layer enables this portion to absorb more water before percolation begins. King has observed in May a difference of 2·3 per cent. of water in the top 3 feet of soil between land ploughed in the autumn and the adjoining land not ploughed ; the gain in this case due to the ploughing was 110 tons of water per acre, or rather more than 1 inch of rain.

The following table shows the effect of ploughing up a stubble in autumn on a thin chalky loam at Wye, Kent, where the soil is only about 2 feet deep. The samples were taken on 3rd March 1902 ; there had been but little rainfall except in the previous December. The figures show mean percentages of water in the wet soil exclusive of stones.

	Land Ploughed in Autumn.	Adjoining Land not Ploughed.
1st foot . .	16·45	16
2nd foot . .	15·8	14·6

Of course, the autumn ploughing has many other beneficial effects in addition to the above-mentioned gain of water ; the ploughed soil gets alternately frozen and thawed, wetted and dried, with the result that on the stiff lands the puddling effects of trampling, etc., are obliterated, and the soil acquires a loose, open texture, out of which a seed-bed can be made. From the point of view of tilth the all-important thing is to get the ploughing done before the frosts are over. However wet the soil may have been during ploughing, if it gets two or three freezings, followed then by drying weather, it will crumble naturally and can be harrowed down to a good seed-bed. But if a clay soil is cultivated when wet and then dries rapidly, as it often will do in March, it forms obstinate clods which no operation will reduce to a good tilth. Again, the additional surface exposed to the action of frost and rain causes increased weathering, and some of the dormant mineral plant food is brought into a more available condition.

There is some difference of opinion about the effect of spring cultivations on soil moisture. The immediate object, of course, is to obtain a seed-bed ; but it was also considered that the loose surface obtained by ploughing and harrowing acted as a mulch to protect the soil from excessive loss of moisture by evaporation by breaking the capillary connexion between the moist subsoil and the surface. But if, as is now held, capillary action can be effective only over short distances, the loss of moisture by capillary rise to the surface can proceed only to a limited extent. Hence, the only conditions under which a soil mulch might be effective in checking evaporation, would be the presence of a water-table within a few feet of the surface. This condition may obtain essentially in many soils with impeded drainage—soils in which, owing to restriction of root development, drought may have serious effects for crops.

It may be conjectured that such conditions explain the conservation of soil moisture actually observed in many experiments as a consequence of a soil mulch. The following figures, obtained by King in the United States, illustrate how a spring ploughing can conserve moisture. The upper line shows the water content of the top 4 feet of a certain piece of land on 29th April, on which date part of it was ploughed and part left untouched. On 6th May, no rain having fallen, the soil was sampled again, both on the ploughed and the unploughed piece, with the results set out in the lower figures :

Lbs. of Water in each successive cubic foot.	1st.	2nd.	3rd.	4th.
Land on 29th April	14·1	20·1	18	16·6
Land on 6th May, ploughed 29th April.	13·9	20·7	18·3	16
Land on 6th May, not ploughed .	10·6	18	17·3	13·9

It is seen that the ploughed land practically lost no water during the week ending 6th May, whereas during the same period the land not ploughed lost 9·1 lbs. per square foot of surface, a quantity equivalent to 1¾ inch of rain.

During recent years, many received opinions on the effect of cultivations have been called into question. Practical men have long believed that hoeing and other surface cultivations could conserve moisture in dry weather. They have also believed that rolling, by consolidating the ground, brought particles into close connexion with the moist subsoil and thus facilitated the supply of moisture to germinating seeds. The view has now been put forward, supported by careful experiments, that the main functions of cultivations are to produce a seed-bed and to suppress weeds, and that cultivations over and above those necessary for these ends, are superfluous. Whilst this view may be valid for certain conditions, such is the variety of soil and climate in our country that further experimental work appears necessary before the new views can be considered established or the older views demolished.

The extent to which the deeper subsoil below the range of the roots of the crop is able to supply the surface soil and the growing plant with water by capillarity has been the subject of considerable discussion. It has been very generally considered that the uplift that must go on from the permanent water-table, at whatever depth, provided the subsoil or underlying rock is of the texture that permits of capillary movements, must be a factor in the supply of water to the crop during protracted periods of drought. It seems probable, however, that the amount so lifted can be of no material service, and that the effective capillary movements are those of comparatively small range, which bring the water in the soil a few inches or even fractions of an inch to the actual surface of the root hairs. In the first place, as indicated above in King's experiments, the rate of capillary uplift diminishes very rapidly as the distance from the water-table is increased. At Rothamsted (p. 87) the two drain-gauges consist of isolated blocks of undisturbed soil, one 18 inches, the other 6 feet deep. The surfaces of both are freely exposed to rainfall and evaporation. Over a long period of years the proportion of the rainfall percolating through and evaporating from the surface of either gauge are identical, except for certain minor differences explicable on other grounds. Thus the water remaining in the deeper layers of the 6-foot gauge, even when saturated after a rainfall, has never been lifted to the surface and evaporated. Again, there would generally seem to be water enough in the layer of soil and subsoil traversed by the roots of the plant to supply the crop with the water it actually uses. The fact that has to be explained is the capacity of a soil to maintain the crop during drought, even to carry it through all its stages of growth without any rainfall, as in certain regions of North America and Australia. On reference to Alway's figures (p. 93) it will be seen that the fallowed land down to a depth of 6 feet had an average of 12·9 per cent. of "free water." Assuming the soil to weigh about three million pounds per acre foot, there would have been approximately 1000 tons of free water down to the 6-foot depth, equivalent to 10 inches of rainfall. This of itself would be sufficient for far more than the average growth made under these conditions. Further, Alway has shown that after a crop, however thoroughly the soil may have been dried out down to the depth (4 to 6 feet) to which the roots of the crop penetrate, yet the layer below will still be moist and possess the same proportion of water that the similar layer contains below uncropped land alongside. Leather has adduced similar evidence from India, and these considerations lead one to conclude that in the main the crop draws for its water supply only upon the zone penetrated by the roots of the plant, and that the movements of water from still lower zones are so small as to be a negligible factor in crop production. It cannot, however, be said that the evidence for this view is complete, and the question merits further investigation.

In any case the freedom of movement of water within the soil by capillarity is a factor of great importance in bringing to the roots the water that is close at hand. In a drought it is always the gravels and coarse sands that suffer first, and this not so much because they start with less water, for we have already seen that what they absorb they can give up almost wholly to the plant, whereas a clay, which absorbs much more, can only hand over about the same proportion to the plant as the sand did, so much being held as hygroscopic moisture. The plant suffers because the small surface of the soil particles gives the coarse-grained sand or gravel a very limited power of moving the subsoil water to the roots of the plant. Should a drought continue, the clay soils begin to suffer next, for though they start with large supplies of water and have an extensive surface of soil particles, yet water can be moved so slowly through the very fine pore spaces that the supply cannot keep pace with the loss by transpiration and evaporation. The soils which are least affected by drought are the deep loamy sands of very uniform texture, fine-grained enough to possess a considerable surface, and yet not too fine to interfere with the free movement of soil water. The root range in these soils is always greater than in clay soils because of their better aeration. The winter penetration of roots into a clay soil is often limited by its temporary saturation with water, and this comparative deficiency in the depth of soil traversed by and supplying water to the roots largely accounts for the manner in which crops on clay soils suffer in a protracted drought. The western soils that the American writers describe as capable of growing wheat with a winter rainfall of 10 to 12 inches and an unbroken summer drought of three months' duration are deep, fine-grained, and uniform, with practically no particles of the clay order of magnitude.

The Drying Effect of Crops

Since a crop transpires about 300 lbs. of water for each pound of dry matter produced, any land that is carrying a heavy crop must contain much less water than the adjoining uncropped land, unless there has been such an excess of rainfall as to saturate the soil in either case. Any summer growing crop, however, especially one of roots, transpires so large a proportion of the customary rainfall during the period of growth that it must leave the soil much drier for its growth. As an example of this removal of water by the growing crop, the following figures obtained at Rothamsted during the very dry summer of 1870 may be quoted, showing as they do the water present in successive 9 inches of fallow and of adjoining land carrying a barley crop. The total difference between the cropped and uncropped land down to the depth of 54 inches, amounted to more than 900 tons of water per acre, or 9 inches of rain, which is quite half as much again as would be accounted for by the crop on the assumption that only two tons or so of dry matter had been grown at the date of sampling :

	Percentages of Water in fine Soil, June 27–28, 1870.	
	Fallow.	Barley.
First 9″ . . .	20·36	11·91
Second 9″ . . .	29·53	19·32
Third 9″ . . .	34·84	22·83
Fourth 9″ . . .	34·32	25·09
Fifth 9″ . . .	31·31	26·98
Sixth 9″ . . .	33·55	26·38

There are two important cases in which the drying effect of vegetation needs to be taken into account, namely, in the use of catch crops and in the planting of fruit trees. On the lighter lands of the south of England catch crops are not uncommonly taken on the land before roots. The stubbles are quickly broken up, and vetches, trifolium, or rye, are sown in time to make a start whilst the land is warm, and to be either cut green or fed off before the land is wanted for turnips in the following spring. The advantages of the practice are that the summer-formed nitrates in the stubble-ground are saved from washing out, and that a valuable bite of early fodder is obtained : with the leguminous crops also, the farm is enriched by the nitrogen gathered from the atmosphere. The difficulty of getting catch crops lies in the fact that the stubble-ground is left very dry by the preceding crop, so that a timely rainfall is needed to obtain a plant. The danger of their use is that they may so deplete the available soil water as to give the succeeding crop of roots a very poor chance of germinating or growing well. In America the practice has been suggested of sowing some leguminous crop like clover in the tillage orchards about the end of July, so that the new surface crop should so dry the ground as to forward the ripening of the apples on the trees ; again, any second growth of the trees due to a late summer rainfall would be prevented, this moisture being dealt with by the catch crop.

The second illustration worthy of notice is that fruit trees when newly planted in grass land often make a very poor growth for a year or two. This is because a fruit tree when planted is but indifferently supplied with water-collecting roots ; inevitably they are few in number and have a very restricted range. Hence they must be in a soil well supplied with moisture if they are to provide the tree with the necessary water, and they are very ill-fitted to compete with a crowd of fibrous grass roots surrounding them, should the season turn out dry. In one experiment the moisture in the top foot of a pasture was found to be only half that present in the top foot of neighbouring uncropped land.

The following table shows the percentages of water in the fine earth of an orchard on heavy soil, part of which was under grass and part kept tilled ; it will be seen that in the winter the grass land carries as much or even more water than the bare soil, but towards the end of the summer the drying effect of the grass becomes very pronounced, even down to the third foot.

	1st 9 Inches.		2nd 9 Inches.		3rd 9 Inches.	
	Grass.	Bare.	Grass.	Bare.	Grass.	Bare.
December 19/05	25·0	24·7	23·5	23·5	25·0	27·0
March 3/06	26·7	23·3	21·2	21·9	20·6	19·6
May 24/06	17·7	24·0	18·7	24·5	22·3	25·0
July 25/06	13·8	15·6	14·5	18·2	14·8	24·4
September 27/06	12·6	15·7	13·8	15·1	15·6	18·8
April 6/07	21·1	21·6	21·0	24·0	19·6	21·3
October 9/07	22·6	27·1	23·7	...	23·6	25·0

Few crops so effectually dry the surface soil as grass does, because of the intimate way in which its roots traverse the soil, hence a fruit tree cannot compete with grass for water as long as the two sets of roots are confined to the same layer. The experiments at the Woburn Fruit Farm of planting fruit trees and sowing the seed of coarse meadow grasses at the same time, show this competition at its highest degree, but even when trees are planted in old pasture, care should be taken to keep a ring round the tree free from grass and well cultivated or mulched for at least two years.

Other causes are doubtless at work ; it has been argued that the grass roots excrete substances toxic to the roots of the fruit trees, among which we may mention carbon dioxide as a very probable factor in checking development. Again, the grass roots may induce an injurious disturbance of the bacterial flora, but it is not possible as yet to discriminate with any certainty among the actions at work. For similar reasons, when trees are planted in arable land, weeds should be kept down ; crops like cabbages or mangolds should not be grown between the rows of trees ; such crops are usually considered to " draw the land " and deplete it of plant food, but the harm they do lies in the water they withdraw just at the most critical season, when the tree is making its first start in its new quarters.

Bare Fallows

The custom of fallowing land, of leaving it entirely bare for a season, during which the land is worked as often as possible, is one of the oldest in agriculture ; a rotation of wheat, wheat, fallow, or of beans, wheat, fallow, being almost universal, until the introduction of turnips gave the farmer a chance of cleaning his land and yet growing a crop at the same time. The objects of a fallow were various : in the first place, the summer cultivations resulted in a thorough cleaning of the land and in a free development of nitrates for the succeeding crop ; also on the heavy soils, which are the most suited to fallowing, a good tilth was obtained that was often impossible otherwise. Indeed, even at the present day it is found desirable and even necessary to introduce an occasional bare fallow when farming on the heavy clays of the south and east of England, in order to obtain a satisfactory tilth in that dry climate.

One of the most notable effects of fallowing lies in the production of a stock of nitrates from the stores of combined nitrogen in the soil ; these nitrates are at once available for the ensuing wheat crop if the autumnal rains are not too great to wash them out of the soil (see p. 111).

But in addition to the gain in available nitrogen due to fallowing, the land which does not carry a crop during a season will accumulate a store of water which may be of the utmost service to the succeeding crop. In the preceding section some figures have been given showing how much more water is present at the end of the summer in the fallow land than in the land which had carried a crop, so that in districts where the winter rainfall is small the fallowed land will start the next season with a great advantage. Indeed, in a semi-arid climate where the annual rainfall is insufficient, satisfactory crops may yet be grown in alternate years by using an intermediate fallow period in which to accumulate a reserve of subsoil water.

At Rothamsted, portions of the wheat field were fallowed during the summer of 1904, and the following table shows the percentage of water in the fine earth on 13th September, 2·849 inches of rain having fallen since the crops had been cut :

	Unmanured.		Dunged.		Mean of 8 Plots.	
	Cropped.	Fallow.	Cropped.	Fallow.	Cropped.	Fallow.
1st 9″ . .	15·8	16·0	20·2	19·3	17·4	17·2
2nd 9″ . .	18·9	19·8	14·5	17·0	18·8	20·0
3rd 9″ . .	20·8	23·3	13·7	18·4	20·1	22·3
4th 9″ . .	23·1	25·2	15·5	19·7	20·9	23·1
Mean . .	19·6	20·8	16·0	18·6	19·3	20·6

In the surface layer there is practically no difference, both having become equally wet by the rains after harvest, but in the lower depths the fallow soils are the wetter, and the differences are less pronounced for the unmanured plot where a small crop had been grown than for the dunged plot with its larger crop.

The way in which fallowing land is of benefit to the crop, both by making nitrates and particularly by saving water in a dry season, is easily seen in the superior plant always found on the outside rows or edges of an experimental plot divided from the others by a bare path ; on one side the plant has the benefit of fallow ground as well as of extra space, light, and air, and flourishes accordingly. The Lois-Weedon system of husbandry, where the land was divided into alternate 5-foot strips of corn and cultivated fallow land, was nothing but an application of this principle on a large scale, as indeed is any system of growing a crop in wide rows to admit of some form of hoe or cultivator working regularly at the ground between. In a humid climate or on a porous soil there is great danger of losing the nitrates formed in the summer by washing out during the autumnal and winter rains, nor is there any advantage gained by storing water where the usual winter rainfall is sufficient to saturate the soil. For this reason, in the Rothamsted experiments, the plot growing wheat continuously has given a greater crop per acre per annum than the plot fallowed and sown with wheat in alternate years, though the wheat crop following fallow has always been larger than the crop grown the same year on the unmanured plot.

Average Crop.	Wheat every Year.		Fallow and Wheat.	
	Grain.	Straw.	Grain.	Straw.
	Bushels.	Lbs.	Bushels.	Lbs.
1856–1895 . .	12¾	1127	8⅝	798

Of course the average yield on the fallowed ground was twice the above figures, i.e., 17⅜ bushels of grain and 1595 lbs. of straw, but it was only grown every alternate year.

That the autumnal rainfall is the great factor in determining whether a bare fallow shall be profitable or not to the following crop, may be well seen by a further examination of the results obtained at Rothamsted on these plots, by comparing the crops with the percolation which took place in the autumn previous.

The percolation through 60 inches of bare soil for the four months, September to December inclusive, as measured by the drain-gauge previously described on p. 87, amounted on the average to 6·45 inches for the 31 seasons, 1870–1901. If, then, we divide the harvest years into two groups according as the autumnal percolation is above or below the average, and allot to each year the crops on the continuous wheat and wheat after fallow plots for the harvest following the given percolation, we shall obtain the following average results, which show in group 1 the mean crops following autumns of less than average percolation, and in group 2 those following autumns of comparatively high percolation. The percolation is given in inches, the crops in lbs. per acre of total produce, both grain and straw; and as further evidence of the extent of percolation, the average number of days are given during the four months on which water ran from the tile drain underlying the continuous wheat plot.

		Rainfall.	Percolation through 60-inch gauge.	No. of days on which tile drain ran.	Crop, lbs. per acre.		
					Wheat after Wheat each Year.	Wheat after Fallow.	Gain due to Fallow.
1.	15 Years of Percolation below average .	8·94	3·99	4	1807	2677	870
2.	16 Years of Percolation above average .	13·78	8·92	13	1627	1757	130

Thus the bare fallow which increased the succeeding crop above that given by the continuous wheat plot by nearly 48 per cent. in the seasons when a comparatively dry autumn succeeded the fallow, increased it by less than 8 per cent. when there was much percolation after the fallow.

It follows, therefore, that the practice of fallowing land is only an economical one where the annual rainfall is low and where the land is too strong to admit of free percolation; it is, however, admirably adapted to the successful cultivation of clay land in dry, hot climates.

"*Dry Farming*"

The practice of fallowing finds its greatest development in the system of "dry farming," which has been evolved in semi-arid regions, such as the Great Plains of North America and parts of Australia and South Africa, in order to deal with land with an average rainfall of from 15 to 10 inches. There, the amount of water reaching the soil is insufficient to provide for the needs of a crop every year. Failures are too numerous to allow the farmer to make a living; but it is found to be possible to obtain a crop with some certainty if it is preceded by a year of bare fallow, during which the greater part of the rainfall is accumulated for the succeeding year's crop. The bare fallow may be necessary in alternate years or may be taken every third year. For example, the regular course of cultivation on the wheat lands of South Australia, in the zone with an annual rainfall of from 12 to 20 inches, begins with a year of bare fallow, during which the ground is worked over three or four times, as often as is necessary to keep the surface loose. Then follows the wheat which is harvested by a machine that simply strips off the heads and leaves the straw standing. Sheep are then turned in and graze upon the straw and upon such weeds as may come up spontaneously during this the third year of the rotation. With better farming, especially where the rainfall is rather greater, peas may be sown on the stubble to be grazed off in the third year, thus enriching the soil in nitrogen as well as providing increased food for the sheep. But the ground is left by the wheat too dry for a substantial fallow crop, which in its turn would endanger the accumulation of the scanty rainfall for the ultimate wheat crop. In Australia the wheat is autumn sown, and the farmer's routine consists in spending the late autumn and early winter in ploughing and sowing for wheat. During spring and summer he is occupied in going regularly over the fallow land, with appropriate intervals for sheep shearing and harvest. On the Great Plains the land is frost-bound during the long winter, and the wheat is spring sown ; sheep are not kept because of the cold, but otherwise the routine of cultivation is identical. The Australian is generally content with ploughing the bare fallow repeatedly ; in America the methods are a little more elaborated, and subsoil packers, followed by disc harrows and other surface cultivators, are employed in order to conserve moisture and prevent evaporation, by maintaining a firm substratum and a live surface. These simple principles of " dry farming," founded upon the practice elaborated in the drier districts of the south and east of England, have enabled vast tracts of otherwise scanty grazing country to be brought under cultivation[1]. The details of the methods to be followed, and the crops that can be grown, are being made the subject of careful investigation, now that the better farming lands are all taken up, and new settlers are being forced on to what before were ranching areas or regarded as bad lands. What are wanted are crops which elaborate a maximum of dry matter for the water they consume or, if cereals, which transform a comparatively high proportion of their total dry matter into grain.

Effect of Dung on the Retention of Water by the Soil

A soil which has been enriched in humus through repeated applications of farmyard manure will resist drought better than one in which the humus is low ; the difference is seen not so much in the greater amount of moisture present in the soil rich in humus, as in the way it will absorb a large amount of water temporarily during heavy rainfall, and then let it work more slowly down into the soil, thus keeping it longer within reach of the crop. Good examples are afforded by the Rothamsted plots ; samples of soil from the wheat land were taken on 13th September 1904, on the previous day

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[1] In many areas with disastrous results (cf. p. 32).

0·262 inch of rain had fallen, but for nine days before there had been little or no rain. The portions of the plots from which the samples were drawn had been fallowed through the summer, so that the drying effect of the crop was eliminated. Samples were also taken from the barley plots on 3rd October of the same year ; 0·456 inch of rain had fallen on the 30th September, before which there had been fifteen days of fine weather. The following table shows the water in the soil of the unmanured and the continuously dunged plots respectively, as percentages of the fine earth from which the stones had been sifted :

Percentages of Water in Rothamsted Soils

Depth.	Broadbalk Wheat.		Hoos Barley.	
	Unmanured.	Dunged.	Unmanured.	Dunged.
0″ to 9″	16·0	19·3	17·0	20·7
9″ „ 18″	19·8	17·0	22·5	17·7
18″ „ 27″	23·3	18·4	22·1	18·3

It is thus seen that in both cases the dunged soil, rich in humus, had retained more of the comparatively recent rainfall near the surface, so that the top soil was moister whilst the subsoil was drier. The difference in favour of the surface soil was about 3·5 per cent., which on that soil would amount to about 30 tons per acre, or approximately 0·3 inch of rain. It is thus seen that the surface soil of the dunged plot had retained practically the whole of the preceding rainfall ; and the greater dryness of the subsoil was due to the way the soil had kept back the small rainfalls, which had been evaporated instead of passed on to the subsoil as they had been on the unmanured plots. The same fact is illustrated by the behaviour of the drains which run below the centre of each of the wheat plots at a depth of 30 inches ; below the dunged plot the drain very rarely runs, only after an exceptionally heavy and long-continued fall, whereas the drain below the unmanured plot runs two or three times every winter. Putting aside the greater drying effect of the much larger crop on the dunged plot, the difference is mainly due to the way the surface soil rich in humus first of all absorbs most of the water, and then lets the excess percolate so much more slowly that the descending layer of over-saturation, which causes the drain to run, rarely or never forms.

The water-retaining power of the dung may also be seen in the superior yield of the dunged plots in markedly dry seasons. The next table shows a comparison of the yield on plot 2, receiving 14 tons of dung, and plot 7, receiving a complete artificial manure, for the years 1879, which was exceptionally wet and cold, and 1893, which was hot and dry throughout the growing period of the plant. The rainfall for this period, i.e., for the four months March to June, was 13 inches in 1879 and only 2·9 inches in 1893.

WHEAT. YIELD IN BUSHELS OF GRAIN.

Plot.	1879.	1893.	Average 51 Years.
2	16·0	34·25	35·7
7	16·25	20·25	32·9

The average yield on the dunged plot is about 3 bushels more than on plot 7, but in the dry year its superiority amounted to 14 bushels, whereas in the very wet year the two plots sank to the same low level. In a bad season the bacterial changes which render the plant food in dung available for the crop go on very slowly.

CHAPTER VI

THE TEMPERATURE OF THE SOIL

Causes affecting the Temperature of the Soil—Variation of Temperature with Depth, Season, etc.—Temperatures required for Growth—Radiation—Effect of Colour—Specific Heat of Soils—Heat required for Evaporation—Effect of Situation and Exposure—Early and Late Soils.

THE active growth of a plant is practically suspended below a certain temperature, which is about 41° F. for the majority of cultivated plants ; all the various changes which are essential to the development of the plant, such as germination, vegetative activity, and the bacterial processes in the soil, show a similar dependence upon temperature.

These vital actions cease below a certain minimum, above which they usually increase with the temperature until an optimum is reached, when the action is at its greatest : beyond this point the action decreases until a superior limit is reached, which again suspends all change. It therefore becomes important to study the manner in which heat enters and leaves the soil, because upon the temperature acquired depend such practical questions as the suitability or otherwise of the land for particular crops, the season at which to sow, and the earliness or lateness of the harvest.

The surface soil receives heat in four ways :

(1) By direct radiation from the sun, whose rays, both of light and of invisible heat, are absorbed and raise the temperature of the absorbing soil.

(2) By precipitation, as in the spring when warm rain enters the ground and brings with it a considerable quantity of heat, or when aqueous vapour in the air is condensed on the colder soil.

(3) By conduction from the heated interior of the earth a small amount of heat reaches the surface.

(4) By the changes which result in the decay of the organic material of the soil, when as much heat is developed as if the same material had been burnt in a fire.

The surface soil loses heat :

(1) By radiation ; like any other body possessing heat the surface of the soil is always emitting invisible radiant heat, which may, or may not, be counterbalanced by the corresponding radiations it is absorbing.

(2) By conduction either to cooler layers of earth below or to cooler air above.

(3) By the evaporation of the water contained in the soil ; at ordinary temperatures the evaporation of 1 lb. of water would absorb enough heat to lower the temperature of about 7,500 lbs. of soil by 1° F.

The actual temperature attained by a given soil at any time depends upon the relative effect of the heating and cooling actions set out above.

Variation of Soil Temperatures with Depth, Season, etc.

Fig. 11 shows the monthly mean temperatures of the soil at 6 inches, 3 feet, and 6 feet respectively, as compiled from readings taken at 9 a.m. at Wye during 1896, the soil being a light well-drained loam under grass. It will be seen that the variations in temperature diminish with the depth ; in fact a point is soon reached, about 50 feet down, below which the effect of the gain or loss of heat at the surface is inappreciable, and the temperature is constant from day to day, only increasing with the depth, according to the well-known law. Each curve cuts each other curve at least twice ; for a certain period the upper layer is giving, and during the rest of the year, receiving heat from the layer above or below. The maximum temperature attained at a depth of 3 feet comes a little later in the year than the maximum for 3 inches, and the maximum at 6 feet lags still further behind, owing to the slowness with which the heat is conducted. It will be seen that the curve indicating the temperature at 6 inches (and the mean figures for 3 and 9 inches are almost identical) does not reach the 41° F. required

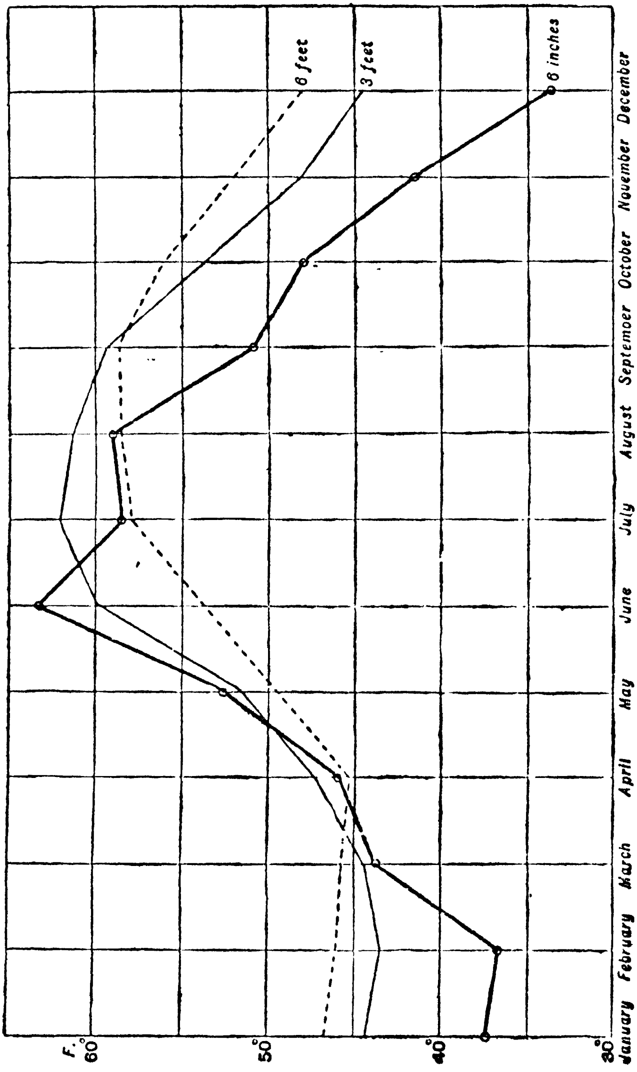


FIG. 11.—Soil Temperatures at 9 a.m., Monthly Mean, 1896.

for the beginning of vegetative growth until April; it is, however, constructed from monthly averages only, and from observations taken at 9 a.m. when the surface soil has been considerably cooled during the night. Much higher temperatures are attained during certain parts of the day even in the early spring months, otherwise no germination could take place; these diurnal and hourly fluctuations are, however, chiefly confined to the surface soil. Fig. 12 shows the daily results during a fortnight of April 1902, and Fig. 13 certain hourly readings obtained in the same month, in this case beneath smooth, well-worked arable land. The diurnal variations die away before the depth of 3 feet is reached, nor are hourly variations perceptible at the depth of one foot, except in the case of heavy precipitation and a pervious soil. It will also be noticed from the last curves that during part of the day the temperature at the depth of 6 inches ran up to a point well above the minimum required for germination, although the mean soil temperature at 9 a.m. was near that limit.

Temperatures required for Growth

Reference has already been made to the fact that a certain temperature is necessary before the vital processes involved in growth become active; this temperature is not always the same, but may be considered to lie between 40° and 45° F. for most of the plants grown as crops in this country.

The following table shows minimum, optimum, and maximum temperatures of growth for a few plants:

	Minimum.	Optimum.	Maximum.
Mustard . . .	32° F.	81° F.	99° F.
Barley . . .	41	83·6	99·8
Wheat . . .	41	83·6	108·5
Maize . . .	49	92·6	115
Kidney Bean . .	49	92·6	115
Melon . . .	65	91·4	111

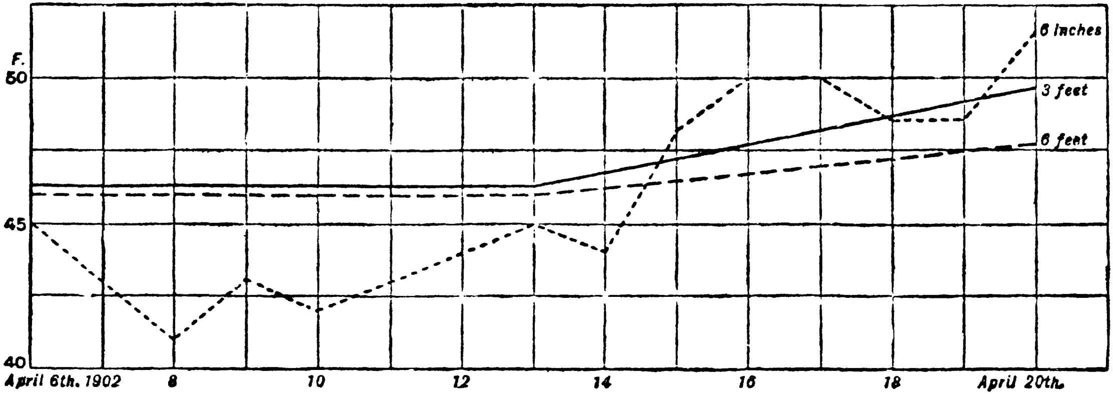


FIG. 12.—Soil Temperatures at 9 a.m., Daily Readings.

The next table shows the effect of soil temperature upon the growth of the root of maize :

ROOT GROWTH OF MAIZE IN 24 HOURS.

Temperature.	Millimetres.
63° F.	1·3
79	24·5
92	39
93	55
101	25·2
108·5	5·9

The osmotic absorption of water by the roots of a plant is much affected by the temperature of the soil ; although some plants, like cabbage, will continue to take in a little water even near freezing-point, others require a higher temperature ; for example, Sachs has shown that tobacco and vegetable-marrow plants will wilt even at night, when transpiration is very small, if the temperature of the soil falls below about 40° F.

The killing of plants like rose-trees during frost is generally due to drying out from this cause rather than to the actual cold. As the air is often very dry during a frost, evaporation continues, especially if a wind be blowing at the same time ; thus the exposed shoots of the plant are losing water which is not being replaced by the roots, whose action is suspended by the low temperature. A covering of snow or dead leaves, or even the protection afforded by a little straw, bracken, or spruce boughs, prevent the destruction of the plant, not by keeping it so much warmer, but by protecting it from evaporation.

The connexion between soil temperature and vital processes is perhaps most apparent in the case of germination, for which not only is a certain minimum temperature requisite, but for several degrees above this minimum the germination is so slow and irregular that the young plant is very liable to perish while remaining in such a critical condition. The

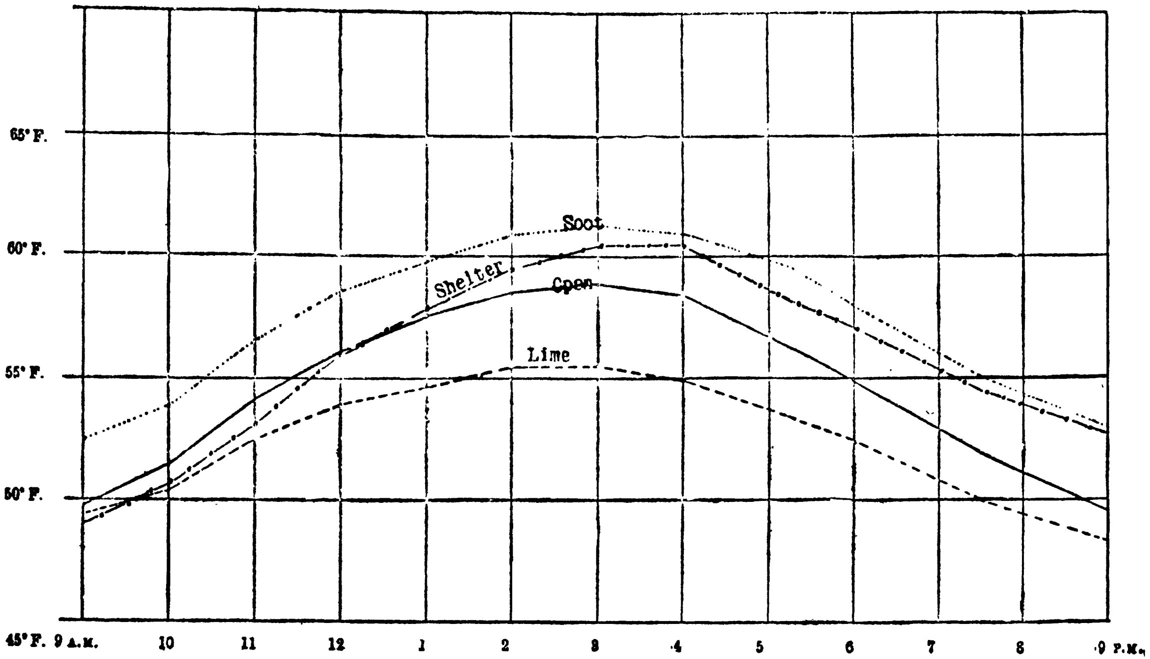


FIG. 13.—Soil Temperatures at 6 in. depth, as affected by the state of the surface. Sun with strong N.E. wind. 27/iv/02.

following table shows the range of temperatures for the germination of various cultivated plants.

TEMPERATURES OF GERMINATION.

	FAHRENHEIT.		
	Minimum.	Optimum.	Maximum.
Wheat	32° to 41°	77° to 88°	88° to 110°
Barley	40°	77° to 88°	100° to 110°
Oats	32° to 41°	...	88° to 100°
Pea	38° to 41°	...	...
Scarlet Runner. . .	49°	91°	115°
Maize	49°	91°	115°
Cucumber, Melon, etc. .	60° to 65°	88° to 99°	110° to 120°

The practical bearing of these figures is obvious; it is necessary to sow some seeds, like the melon, in heat, and to defer the seeding of other crops, like mangolds or maize, until the ground has acquired not only the temperature necessary for germination but one that will ensure a subsequent rapid growth of the seedling plants.

For example, turnips will germinate at almost as low a temperature as barley, but the optimum temperature is higher for turnips; they are therefore sown much later in the spring, when the ground has more nearly reached this temperature, because the seed is small and the young plant very susceptible to insect attacks, so that the turnip seed must germinate and grow away rapidly if it is to succeed.

Under ordinary field conditions much of the nutrition of the crop depends upon the activity of certain bacteria in the soil, which break down organic compounds containing nitrogen, and ultimately resolve them into the nitrates taken up by the plant. Most bacteria are active within about the same limits of temperature as have been indicated above for the higher plants; the nitrification bacteria, for example, cease their work below 41° F. and above 130° F., their optimum temperature being about 99° F.

The way a low temperature will check the production of nitrates until they are inadequate for the needs of the crop is often seen in the spring, and may be connected with the yellow colour of the young corn during a spell of cold and drying east wind.

Radiation

The main source of the soil warmth consists in the heat received from the sun by radiation; this, according to Langley, amounts to about 1,000,000 calories per hour per square metre of surface from a vertical sun in a clear sky. Supposing this energy were wholly absorbed by a layer of dry soil 10 cm. thick, its temperature would rise by as much as 90° F. in an hour. Of course in nature many other factors are at work to reduce this temperature; the sun is rarely vertical, the soil material does not completely absorb but reflects some of the sun's rays unchanged; at the same time it is always radiating in its turn rays of lower pitch than the majority of those received. The latter rays are easily caught by many substances, glass and water vapour in particular, which are transparent to the rays of higher refrangibility proceeding from the sun. A greenhouse, for example, is practically a radiant heat trap; the temperature inside runs up because the sun's rays of light and heat can penetrate the glass, whereas the obscure heat rays radiated back again from the warmed-up surfaces inside the house are not able to pass through the glass again. Just in the same way the temperature rises and the sun's heat becomes oppressive when the air is laden with water vapour, because it retains the radiations emitted by the surfaces heated by the sun. *Per contra*, the temperature of the ground falls more rapidly at night when the sky is clear and the air dry, for then there is no blanket of cloud or water vapour to arrest or reflect the radiations from the surface.

Effect of Colour

The ability of soils to absorb the sun's rays depends very much upon colour: with black soils the absorption is almost complete; it is greater for red than for yellow soils, least of all for those which look distinctly white or light coloured. It has already been shown that the colour of soils depends mainly upon humus and hydrated ferric oxide, the latter accounts for all the red, yellow, and brown shades, the former for the black coloration of the soil. Deep-seated clays are often blue or green, due to various ferrous silicates or to finely divided iron pyrites, which afterwards oxidize to brown ferric oxide. The more finely grained a soil is the more surface it possesses, and the greater the amount of colouring matter that is required to produce a given colour ; a coarse sand is often quite black though it contains but a small percentage of humus.

Though the colour of a soil affects the rate at which it absorbs heat, it does not follow that the dark soils will lose with a corresponding rapidity when radiation is taking place at night ; the emissive power of the substance for rays of low refrangibility, such as are emitted at ordinary temperatures, is not affected by colour. Hence, the extra heat gained by a dark soil is retained and not lost by a corresponding increase in its radiating power.

The curves in Fig. 13 show the temperatures of the soil at a depth of 6 inches during an April day with a bright sun and a strong drying wind. The land was a light loam of a grey-brown colour when dry ; it had been cultivated, rolled, and the surface hoed over before the thermometers were inserted ; on plot 1 the bare ground was left untouched, plot 2 received a dressing of soot until the surface was black, plot 3 was similarly whitened over with lime. It will be seen that the covering of soot warmed the soil until at 3 p.m., when the maximum temperature was attained, the difference was 2·4° ; this superiority is also retained during the later cooling stages ; even at 9 p.m. the blackened soil was still 2·5° warmer than the bare ground. The whitening with lime had caused so considerable a reflection of the radiant heat that the soil beneath was always 2 to 3° cooler than the bare ground. In carrying out this experiment it is necessary to use no more lime or soot than will distinctly colour the soil ; the results will be disturbed if an excess of either loose powder acts as a mulch.

Specific Heat of Soils

The specific heat of the substances of which soil is composed is comparatively low, ranging from 0·1 to 0·2—i.e., only from one-tenth to one-fifth as much heat will be necessary to raise the temperature of 1 lb. of dry soil by 1°, as would be required to produce the same rise of temperature in an equal weight of water. The humus possesses the greatest specific heat and the sand the least; against this must be set off the fact that the densities of these soil constituents vary in the opposite sense, so that the amounts of heat required to bring about a given rise of temperature to a certain depth in different soils are more nearly equal. The specific heats are, however, small in every case when compared with that of water; hence soils which retain much water will require far more heat to raise their temperature than dry soils would. In consequence, clay and humus soils are cold because the water they retain gives them a high specific heat; they require more of the sun's rays in spring to bring them up to the proper temperature for growth, whilst sandy and other open-textured soils are warm because of their dryness.

If the figures given by Oemler for the specific heats of various soils be combined with their approximate densities and with their minimum capacity for water, the following results are obtained for the specific heats of certain typical soils in a saturated but completely drained condition:

	Specific Heat.		
	Equal Weights.	Equal Volumes.	
	Dry.	Dry.	Wet.
Water	1·0	1·0	1·0
Humus	0·21	...	...
Sandy Peat	0·14	0·11	0·72
Loam	0·15	0·18	0·53
Clay	0·14	0·15	0·61
Sand	0·1	0·125	0·34

The sandy soil only requires about half as much heat to raise its temperature by a given amount as would be needed by the peaty or clay soil, when all the soils are in a wet but thoroughly drained condition ; of course if the clay or peat were inadequately drained, so that a higher proportion of water was retained, their specific heats would approximate still more nearly to that of water.

Just as a clay soil is slow to warm in the spring, its high specific heat causes it to cool correspondingly slowly after the heat of the summer. On clay soils growth will be noticed to continue later into the autumn than on the lighter lands.

Heat required for Evaporation

The coldness of a wet and undrained soil is due, not only to its high specific heat, but to the fact that so much of the heat it receives is spent in evaporating some of its retained water, without causing any rise in temperature. The evaporation of 1 lb. of water at 62° F., i.e., its conversion into water vapour at the same temperature, requires as much heat as would raise the temperature of 1,050 lbs. of water by 1° F., and, if there be no source of external heat bringing about the evaporation, the substance from which the water is evaporated must become cooled to a corresponding extent. The cooling effect of evaporation is well known, but its application to the soil is not always realized ; clays and even more so undrained soils are cold and late, not only because of their high specific heat, but because they retain so much water that can be evaporated. The drying winds of early spring exercise a great cooling effect whenever the soil moisture is allowed to evaporate freely, hence the importance of establishing a loose tilth, if the seed-bed is to warm up the temperatures requisite for germination.

Anything providing a little shelter to check evaporation and break the force of the wind in the spring will have a considerable effect in raising the soil temperature. The dotted curve in Fig. 13 shows the effect of enclosing a plot of the same land with a slight hedge made of spruce boughs about 2 feet high. In the morning the temperature of the sheltered plot was below that of the open ground because of the shading from the direct rays of the sun, but as soon as this effect was over it will be seen that the wind break, by checking evaporation, maintained the soil temperature more than 2° above that of the open ground. Sufficient attention is not given in practice to the value of even slight wind breaks for checking evaporation and so raising the temperature of the soil in early spring. The raisers of specially early vegetables, radishes in particular, on a strip of light land close to the sea in Kent are, however, in the habit of breaking the sweep of wind across their fields by erecting temporary fences of lightly thatched hurdles.

Even the stones upon the surface of the land help. In the *Journal of the Royal Agricultural Society* for 1856, an experiment is described in which the flints were picked off the surface of one plot of ground and scattered over an adjoining plot, with the result that the plot with double its usual allowance of stones was three or four days earlier to harvest than the rest of the field, whilst the plot without stones was a week later still. It will always be noticed how the grass upon a field coated with dung starts earlier into growth, because the loose manure acts as a mulch and protects the soil from the cooling due to evaporation.

Land which is protected from evaporation, and to some extent from radiation, by a layer of vegetation, is always both warmer and less subject to fluctuations of temperature than bare soil.

The warming up of a well-tilled surface soil is increased by the fact that the conduction of heat into the soil below is much checked by a loose condition. A solid body will always conduct heat far better than the same substance in the state of powder, and the more compressed the powder is the better it will conduct simply because there are more points of contact. Hence a rolled and tightened soil will conduct the heat it receives more rapidly to the lower layers than one which is loose and pulverulent. King has shown that, despite the increased evaporation, there is always a higher temperature below a rolled than an unrolled surface.

Sub.

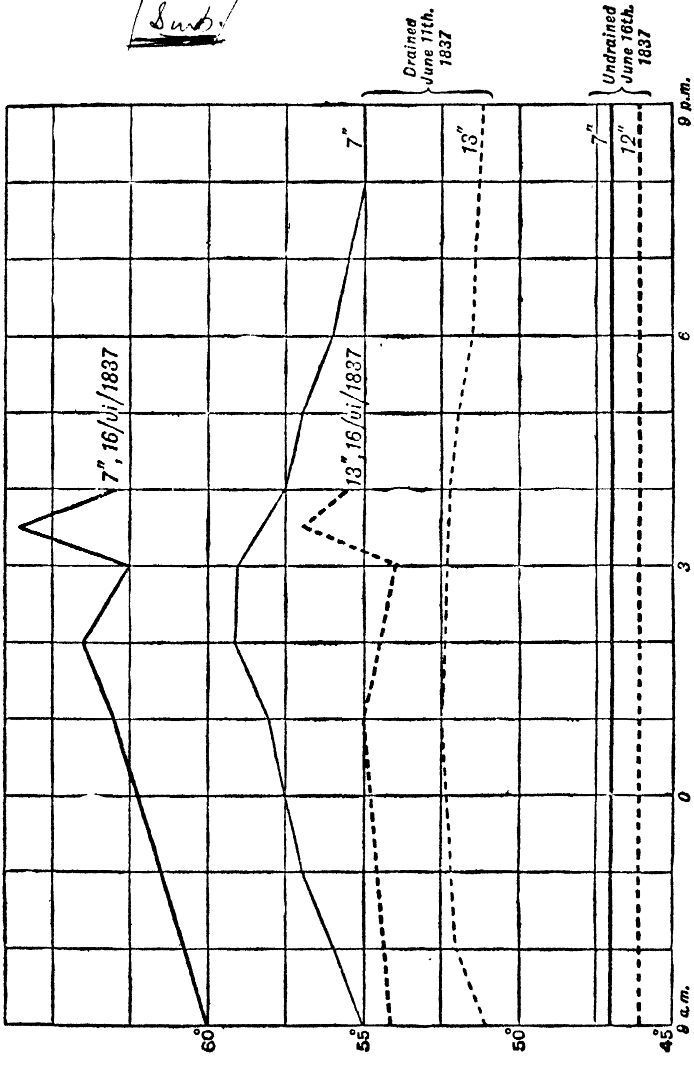


FIG. 14.—Temperatures of Drained and Undrained Bog.

A few observations may be given showing the effect of drainage in enabling the sun's heat to raise the temperature of soil. The curves (Fig. 14) show the hourly temperatures of the drained and undrained portions of a peat bog during two days in June (Parkes, *J. R. Ag. Soc.*, 1844, 142), at depths of 7 inches and 13 inches respectively; the sudden rise of temperature between 3 and 4 p.m. on the second day was due to a thunderstorm, during which heavy rain at a temperature of 78° F. was falling.

The figures in the table below are derived from observations made by Bailey-Denton in 1857 (*J. R. Ag. Soc.*, 1859, 273), on a stiff clay soil situated on the Gault at Hinxworth, the drains being 4 feet deep and 25 feet apart in the drained part. It is noteworthy that the temperature of the air 9 inches above the surface is higher for the drained than for the undrained land, thus supplying further evidence of the cooling effect of evaporation.

MEAN TEMPERATURE ° F. AT 9 A.M.

	A.—Land Drained.			B.—Land Undrained.		
	Air.	At 18".	At 42".	Air.	At 18".	At 42".
March	39·4	40·6	41·7	39	38·2	40·3
April	43	46	44·8	42·4	44	43·8
May	52·9	51	48·4	52·7	48·8	47·1
Mean excess over B.	0·4	2·2	1·2	...	...	...

Effect of Situation and Exposure

Other conditions being equal, in the northern hemisphere the soil temperatures will always be higher on land sloping toward the southern quadrant than with any other aspect. King found a difference of about 3° F. down to the third foot between a stiff red clay soil with a southern slope of 18° and the same soil on the flat; Wollny obtained a mean difference of 1·5° between the north and south sides of a hill of sandy soil inclined at 15°. The chief cause of these differences is the fact that in this country the sun is never vertical, hence a beam of sunlight represented by *xy*, Fig. 15, is spread over an area represented by AB when the ground is flat; if the ground slopes to the south, the same beam is spread over the smaller area represented by AC; if the ground slopes to the north, it is spread over the larger area represented by AD. During the winter half-year, also, the southern slope will have a longer duration of sunlight than the northern slope.

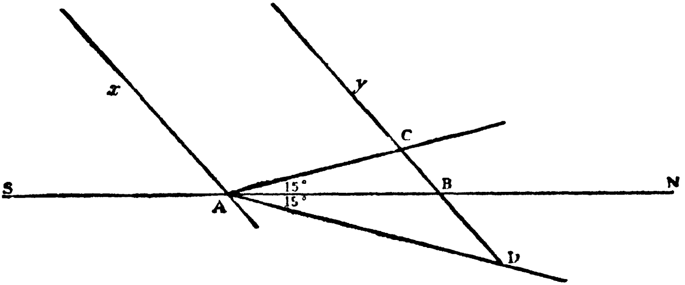


Fig. 15.—Distribution of the Sun's Rays on Southerly and Northerly Slopes.

Though in a general way the temperature both of the air and the soil decreases with elevation above sea-level, yet it is well known that the severest frosts occur locally at the bottom of valleys and hollow places. This is particularly noticeable in the sudden night frosts, characteristic of early autumn and late spring, which are so dangerous to vegetation; it is usual to find the tenderer plants of our gardens, such as dahlias, cut down by frost on the lower levels long before the gardens on the hill are affected. Spring frosts, again, will often nip the early potatoes in the valleys when the higher lands are untouched. Fruit plantations should not be set in the valleys, for no crop suffers more from these unseasonable snaps of cold; so clearly is this fact recognized, that in some fruit-growing districts only above a certain elevation is land regarded as suitable for fruit, and commands a higher rent in consequence. Two causes co-operate in producing the excess of cold at the lower levels. The night frosts in question are always the result of excessive radiation when the sky is clear and the air still. The ground surface loses heat rapidly and cools the layer of air above; the cold air thus produced is denser, and proceeds to flow downhill and accumulate at the lower levels. There is thus a renewal of the air above the higher slopes, and the effect of radiation is mitigated by the inflow of warmer air; at the bottom no change of air is produced and the radiation proceeds to its full effect.

At the same time the vegetation in the valley is generally more susceptible to a frost; the greater warmth by day, together with the extra moisture and shelter, induce an earlier and a softer growth.

Observations of the minimum temperature on the grass made at two stations on a gentle slope of the downs at Wye, about a mile apart and differing in level by 100 feet, showed during a period of thirty-six days in February and March 1902 (which was exceptionally calm and mild), a mean difference of 1° in favour of the upper station; but on two occasions the lower thermometer fell to 24·5° and 21·5°, when the upper thermometer was 30·5° and 29·5° respectively.

The following curves (Fig. 16) show the daily maxima and minima of the air temperatures of 4 feet from the ground for a few days before and after the occurrence of a disastrous late spring frost in May 1902. One station, A, was in a river meadow about 100 feet above sea-level, the second, B, was on a terrace about 50 feet higher and half a mile away; the third, C, was on the flat summit of the down, 500 feet above sea-level and about 1½ mile from the first station. It will be seen that the river-side station gave always the highest maxima during the period and the lowest minima, showing on the one occasion 11° of frost.

Early and Late Soils

From all the considerations developed above it will be seen that an early soil is essentially a coarse-textured and well-drained one. Such a soil retains little water, thus possessing

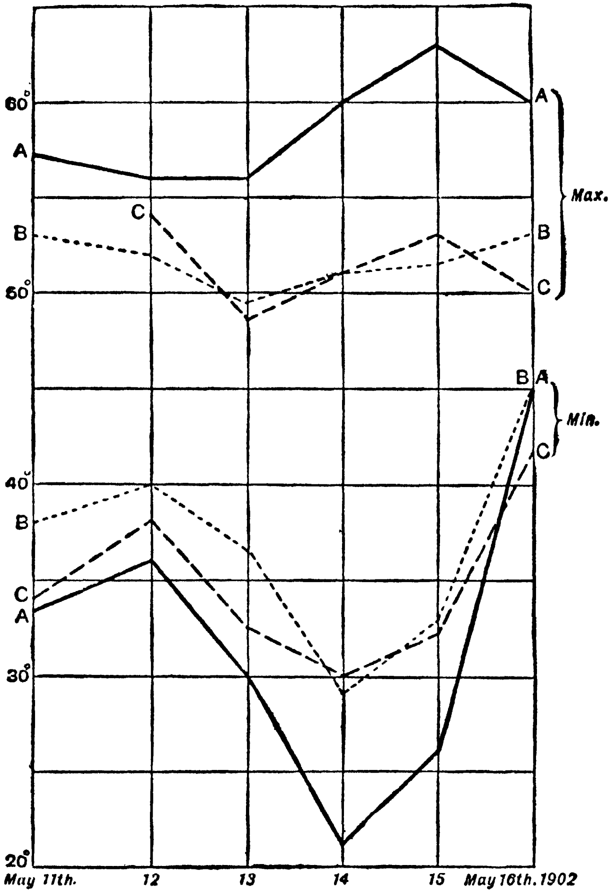


FIG. 16.—Temperatures (Maximum and Minimum) at Various Altitudes.

A = 100 feet. B = 150 feet. C = 500 feet.

a low specific heat, and is easily warmed ; at the same time the low water content gives rise to less evaporation at the surface, and this great cause of cooling is minimized. The dryness of the soil permits of early cultivation, which, by cutting off the access of subsoil water and diminishing the conduction of heat from the surface, quickens the warming up of the seed-bed. The early aeration and warming of the soil promotes the nitrification which is also necessary to growth. If, further, the soil be stony, the conduction of heat from the surface layer into the soil is more rapid, solids being better conductors than powders. Such soils, again, are generally dark coloured, because on the comparatively small surface exposed by the coarse grains the same proportion of humus has a greater colouring effect

These conditions are generally fulfilled by sandy alluvial soils bordering the larger rivers ; in the neighbourhood of large towns, which are generally situated on a river, they form the typical market-gardening soils. At the same time these soils have their disadvantages ; both from their nature and their situation they are subject to rapid changes of temperature ; they suffer much from night frosts both in spring and autumn, and dry out easily in the summer, so that some crops do not come to their full growth. Autumn planted vegetables grow away rapidly, and are apt to become " winter proud " and killed by severe weather.

Of course, to ensure the maximum of earliness and freedom from spring frosts, the geographical situation and the climate must be considered as well as the nature of the soil. The neighbourhood of the sea or any large body of water has a great effect in equalizing the temperatures and preventing severe frosts ; in the British Islands, for example, the earliest potatoes are grown in Jersey, near Penzance, and on other light land along the southern coast of Cornwall, and again, a little later near the sea in Ayrshire. Light land round the coasts of Kent and Essex, which borders, and in some cases is almost surrounded by the sea, is also specially valued for the growth of early vegetables.

The soils naturally retentive of water are late, both because they dry slowly and are rarely fit to work early in the year, and because the high water content keeps their temperature down. Except in long-continued droughts they maintain a supply of water to the plant, their high specific heat keeps them at a comparatively equable temperature and prevents them from cooling down so soon when the summer heats are past. In consequence, the crop is neither forced early to maturity nor is growth checked so soon in the autumn ; the period of development is prolonged until in some cases the season becomes unsuitable for ripening. Many subtle differences may be noticed between the quality of produce grown upon early and late soils ; for example, a comparison made by the author (A. D. H.) of the same variety of apple grown upon adjoining clay and sandy soils showed that the apples from the clay land were smaller and greener, but contained a greater proportion of sugar and acid, and possessed a higher aroma than the apples grown upon the lighter and earlier soil. Wheat grown on the clays is generally of better quality and "stronger" than that yielded by the lighter soils ; whereas the lighter soils yield the finer barley, in which carbohydrates and not nitrogenous materials are characteristic of high quality. On a light soil, becoming both warm and dry early in the season, the plant ceases the sooner to draw nutrient material from the soil ; assimilation, however, continues after the plant has ceased to feed ; finally, maturation—the removal of the previously elaborated material into the seed—begins earlier and can be more thoroughly accomplished. Hence grain from an early soil is, on the whole, characterized by a higher proportion of carbohydrate to protein, always provided that no excessive or premature drying-out has taken place, for that ripens off the grain before the transference of starch has been completed.

It is impossible, however, in the present state of our knowledge to disentangle the effects of the soil proper from the other factors of climate and environment. Thus in considering the composition and quality of grain, whilst the varying chemical composition of different soils, whether natural or due to manuring, has little effect upon the character of the grain, variations in the water supply and the sequence of temperature produce marked changes in the product. For example, the wheats coming from regions possessing a " steppe " climate, with rainfall in the growing season followed by increasing desiccation and high temperatures, are generally hard and translucent and possess a high protein content. Typical examples are the Hungarian, Manitoban, and some of the Southern Russian wheats. On the other hand, wheats grown in climates possessing a winter rainfall, even if followed by a completely dry summer, are soft and mealy, possess a low protein content, and yield flour of much lower " strength " from a baker's point of view.

Climate is more potent than any other factor in causing variations in the composition of wheat. Leclerc and Leavett grew the same varieties of wheat in three localities with widely differing climates, and in the next year grew on seed from each locality at all three places, with the following results as regards protein content :

Year.	Origin of Seed.	Protein in Seed.	Protein in Product grown in		
			Kansas.	California.	Texas.
1906	Kansas . .	16·22	19·13	10·38	12·18
1907	Kansas . .	19·13	22·23	11·00	16·97
1907	California .	10·38	22·23	11·33	18·22
1907	Texas . .	12·18	22·81	11·37	18·21

Thus the seed of Kansas origin containing 19·13 per cent. of protein, when grown in California in 1907 yielded grain only containing 11·00 per cent. of protein ; whereas in the same year seed from the same original stock, but grown in California in 1906 and containing only 10·38 per cent. protein, when moved back to Kansas yielded grain containing 22·23 per cent. of nitrogen.

CHAPTER VII

THE CHEMISTRY OF SOILS

Soil a Complex Mixture—Clay-humus Complex : Clay ; Humus—Base-exchange Reactions—Base-exchange and Soil Acidity—Hydrogen Soils—Sodium Soils—Anionic Exchange—Soil Phosphorus—Absorption of Phosphoric Acid—Accessory Soil Constituents : Calcium Carbonate ; Gypsum ; Manganese Dioxide—Composition of Drainage Waters—Time of Application of Manures.

THE soil is a complex mixture of constituents of varying chemical composition and reactivity. In one sense, we may regard the soil as showing a compromise between reactivity and inertness. If the soil were entirely composed of highly reactive material it would rapidly undergo change and cease to be soil at all. If it were entirely composed of non-reactive material it could not furnish plant food for the use of crops. Actually the soil represents a kind of dynamic equilibrium. Reactive constituents are continually being formed by the weathering of minerals and the decomposition of plant residues. These constituents are continually undergoing change and suffering depletion by the demands of growing crops and the losses in drainage. In this respect soil resembles a living organism.

We may in a broad way consider the soil as consisting of an inert framework or skeleton of relatively coarse material clothed with a reactive complex of clay and humus. It is in this clay-humus complex, sometimes referred to as the *colloidal complex*, that most of the reactivity of the soil is seated. When we view the soil as a whole we must also take into account the soil solution and the soil air. We thus have a three-phase system of solid, liquid, and gaseous components with continuously shifting equilibria.

In addition to the clay-humus complex, there may also be present other reactive constituents, which we may term accessory, because they are not necessarily present in all soils. The principal substances in this category are calcium carbonate, gypsum, manganese dioxide, as well as a number of organic and inorganic compounds present as minor constituents.

The Clay-humus Complex

Although there is reason to believe that clay and humus occur in close association, or even in loose chemical combination in the soil, and may be considered as forming a single complex, it is convenient to consider them separately in the first instance.

The Clay Complex.—We may take the clay complex as being for most purposes identical with the clay fraction and with the weathering complex. This is not strictly true, because in the clay fraction there may be small proportions of unweathered minerals of low reactivity. On the other hand, secondary products of weathering having relatively high reactivity may be present in the coarser fractions distinguished by mechanical analysis. In ordinary soils, however, they may be assumed to be identical and when we study the clay fraction isolated in mechanical analysis, i.e. particles less than 0·002 mm. in diameter we are in effect studying the weathering complex and also the reactive clay constituent of soils.

Recent investigations have shown that the essential constituents of the clay complex are certain plate-like crystalline minerals. With these minerals may be associated amorphous material of similar but indefinite composition, colloidal silicic acid, and hydrated sesquioxides.

The clay minerals fall into three groups, namely (1) the *kaolinite* group ; (2) the *pyrophyllite-montmorillonite* group ; and (3) the *hydrous mica* or *illite* group.

The ideal composition of the kaolinite minerals is $R_2O_3 . 2SiO_2 . xH_2O$ (where $R = Al^{III}$ or Fe^{III}). Isomorphous replacement of aluminium by ferric iron and of aluminium by silicon may yield a range of minerals of varying composition, but of the same essential crystalline constitution. The kaolinite minerals predominate in clays formed by primary weathering of acid and intermediate crystalline rocks under humid conditions. Kaolinite is the characteristic mineral of kaolin or china clay.

The montmorillonite-pyrophyllite group of minerals are based on an ideal formula $R_2O_3.4SiO_2.xH_2O$. Isomorphous replacements occur as in the kaolinite group. Aluminium may also be replaced by magnesium. The montmorillonite minerals can take up water reversibly between the layers of the crystal lattice, which thereby become more widely separated, so that the crystals "swell." Among the minerals of this group are *beidellite*, $Al_2O_3.3SiO_2.xH_2O$ and *nontronite* $Fe_2O_3.3SiO_2.xH_2O$. The minerals of the group have in a high degree the property of combining exchangeable cations, calcium, magnesium, potassium, and sodium. They occur in unaltered aqueous sediments, such as recent alluvia and similar deposits that have not undergone heat metamorphism and recrystallization. They are also present in the products of the weathering of all rocks under arid conditions, and of the weathering of basic rocks under humid conditions.

The minerals of the hydrous mica or illite group are related to the micas of primary rocks in constitution and composition. They may, indeed, be alteration products formed by the weathering of potash and soda felspars. The ideal formula has been given as $K_2O.3Al_2O_3.6SiO_2.2H_2O$. but doubtless, extensive isomorphous replacements occur, including the replacement of potassium by sodium. These minerals occur in sedimentary rocks and to some extent also in products of primary weathering.

Although the montmorillonite minerals are the most reactive, the minerals of the other groups are by no means unreactive and contribute appreciably to the base exchange properties of soils in which they occur. Minerals of the kaolinite group have been shown to be active in "fixing" phosphate in insoluble forms.

Free oxides and hydrated oxides of aluminium and ferric iron occur in association with the clay complex in most soils. The oxides of iron, e.g. haematite, Fe_2O_3, and goethite, $FeO(OH)$, impart the red, orange, and yellow colours to soils. The principal aluminium hydrous oxides are gibbsite, $Al(OH)_3$, and diaspore, $AlO(OH)$.

Titanium and phosphorus also enter into the composition of the clay complex, but more knowledge is needed of their mode of occurrence.

Finally, with the clay complex may be associated colloidal silicic acid and amorphous complexes of similar composition to the clay minerals. These may be of comparatively recent origin and constitute a reactive fraction of the clay complex associated with humic substances also of recent origin.

Silica-sesquioxide Ratios.—The composition of the clay fraction varies considerably, depending on the character of the parent material and the conditions of soil formation. It may vary also within the different horizons of the profile. The following are some typical data for the composition of the clay from different soils :

	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	CaO	MgO	K_2O	Na_2O	Si/Al	Si/R
I.	58·9	17·3	20·8	*	0·2	2·4	1·2	*	5·78	3·27
II.	44·1	27·6	21·8	*	0·6	1·6	1·1	1·0	2·72	1·81
III.	33·95	36·1	11·0	0·6	0·3	0·4	0·6	0·4	1·60	1·34
IV.	10·2	15·8	62·5	0·2	0·2	0·05	tr.	tr.	1·09	0·31

* Not determined.

I. Black clay loam, Transvaal.
II. Granitic drift soil, Aberdeen.
III. Red clay, Georgia, U.S.A.
IV. Lateritic clay, Cuba.

It will be seen that the four examples show decreasing content of silica and increasing content of sesquioxides. A convenient method of expressing the composition of a clay is by means of the molecular SiO_2/Al_2O_3 and SiO_2/R_2O_3 ($= Al_2O_3 + Fe_2O_3$) ratios. The way in which these are derived may be illustrated from the figures for I. In each case the percentage is divided by the molecular weight. Thus,

$$\begin{aligned} SiO_2\ 58{\cdot}9 &\div 60 = 0{\cdot}982 \\ Al_2O_3\ 17{\cdot}3 &\div 102 = 0{\cdot}170 \\ Fe_2O_3\ 20{\cdot}8 &\div 160 = 0{\cdot}130 \end{aligned}$$

Then,

$$\begin{aligned} SiO_2/Al_2O_3 &= 0{\cdot}982/0{\cdot}170 &&= 5{\cdot}78 \\ SiO_2/R_2O_3 &= 0{\cdot}982/(0{\cdot}170 + 0{\cdot}130) &&= 3{\cdot}27 \end{aligned}$$

The corresponding ratios for the other clays are shown in the last two columns of the table.

The silica-sesquioxide ratio or the Si/R ratio of the clay, as it is often termed, is a convenient figure for giving an approximate indication of the general character of a soil. We may thus distinguish *siliceous* soils with high Si/R ratio, and *sesquioxidic* soils with low Si/R ratios. Many important soil properties are dependent on whether the soil is siliceous or sesquioxidic. The changes in Si/R ratio down the soil profile can often throw light on profile development. Thus, a podsol has a wide Si/R ratio in the A-horizon and a narrow Si/R ratio in the B-horizon. Examples are given in Appendix II.

The Humus Complex.—Less is known of the compounds present in the humus complex, partly because they are non-crystalline. Although methods for the fractionation of humus have been devised, there remains the major difficulty of isolating humus unchanged from ordinary soils. Accordingly, most of the studies on humus have dealt with the humus of peats.

An older view of humus was that it consisted of a number of humic acids together with humin, which might be of an anhydride character. Acid substances are indeed present, but although certain investigators claimed to distinguish acids such as ulmic acid, crenic acid, apocrenic acid, and fulvic acid, these are not definite compounds but merely fractions isolated by certain chemical reactions. The actual existence of humic acids was for some time in doubt, and the acidic properties were explained as absorption phenomena. Finally, Odèn demonstrated by physico-chemical methods that true acids exist in humus. Their constitution, as indeed that of many natural substances of high molecular weight, remains still undefined. It is probable that they include a range of compounds and they may all be described as complex weak insoluble acids. With the humic acids are associated non-acid complexes, the so-called humins, which can yield acids by hydrolysis.

Humus imparts a dark colour to ordinary soils, and we are accustomed to think of it as a dark-coloured or black substance. It is possible, however, that the dark colour may be due to the presence of a particular dark-coloured or black constituent. Some types of humus, e.g. that of the so-called black earths formed under conditions of high lime status, are very dark. On the other hand, the humus of red tropical soils does not appear to be so dark in colour as the humus of temperate humid soils.

The constitution of humus and humic acids has been the subject of much investigation and is still far from being understood. It appears, however, that it is mainly composed of a fraction formed by the combination of a protein complex with altered lignin. The lignin originates from the fibrous constituents of plant residues, whilst the protein may be derived from microbial protoplasm. The lignin-protein complex, however, shows none of the ordinary protein reactions and unlike the known animal and vegetable proteins, is highly resistant to microbiological attack. Humus, as a whole, may indeed be regarded either as material that has survived such attack or, more probably, as the end-point of the microbiological decomposition of plant residues. It is by reason of this stability to decomposition by soil micro-organisms that it persists in the soil.

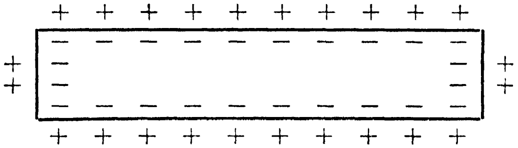
Base-exchange Reactions

The most important and most investigated reactions of the clay-humus complex are those commonly known as *base-exchange* reactions. Their study dates back to 1850, when Way and Thompson published their researches on the reactions of soils with soluble salts. The impetus to the study of these reactions came from the fear that the newly introduced artificial fertilizers would be washed out of the soil and lost in drainage. This fear was not unreasonable, since most of the artificial fertilizers are, in fact, water-soluble.

Way and Thompson showed that ordinary soil possesses the power of withdrawing from solution most of the elements added to the soil as fertilizers, the chief exception being nitrate nitrogen. Some of the salts, like sulphate of ammonia, are decomposed, the base alone being retained and the acid draining through. Way found that liquid manure from a dungheap, which contains both organic and ammoniacal forms of nitrogen and potash, and a little phosphate, when filtered through a short column of soil, parted with almost the whole of its organic matter and much of its salts to the soil ; compounds of calcium were, however, more abundant in the filtered liquid than before. Way's observations were extended by Voelcker, who compared the absorbing powers of different types of soils, and so obtained an idea of the method by which the absorption of each substance was effected ; and later researches have only served to confirm the results then obtained. It was found that all the organic compounds of nitrogen, ammonia—either free or in combination,—phosphoric acid, and potash were almost wholly removed from solution by ordinary soil, though some soils were more effective than others ; whereas nitrates, sulphates, chlorides, and, among bases, sodium and calcium, were only slightly, if at all, retained. These results are confirmed by the analysis of the water which flows from land drains under normal conditions ; this will generally be found to contain nitrates (sometimes in fair quantity), sulphates, and chlorides of calcium and sodium, and considerable amounts of calcium bicarbonate, but rarely more than a trace of ammonia, phosphoric acid, or potash. The importance of Way's investigation was early perceived, for example Liebig saw in it the explanation of the failure of the "mineral manures" he had introduced, which he had so compounded as to be insoluble in water lest they should be washed out of the soil. But the full significance has only latterly become apparent with the increase of knowledge of the colloids of the soil and particularly with the work on base exchange in soils due to Gedroiz in Russia and Hissink in Holland.

We must return to the conception already indicated (p. 137) of the colloids of the soil as existing as a reactive complex enveloping the finest particles of the soil. At or near the surface of this shell, lie the cations (i.e., the positive elements of a salt)—calcium, magnesium, potassium, and sodium, with, as a rule, some hydrogen-ions, which are combined with the weak humic and silicic acid ions of the complex colloid. When such a system is brought into contact with a solution of a salt, there is an immediate exchange of basic ions ; some of the salt base enters the colloid and an equivalent amount of bases displaced from combination with the colloid, form new salts in solution. If, for example, the salt in the solution is ammonium sulphate the ammonium will enter into the colloid complex and an equivalent amount of calcium will form calcium sulphate in the soil water. With dilute solutions and an excess of soil such as occurs in agricultural practice, the mixture will become neither more acid nor more alkaline ; a strict equivalence will prevail in the exchange of bases. The extent to which the ammonium will be withdrawn from the solution will depend on the relative masses of the bases in the colloids and the base in solution, and upon the " strength " of the acid in the salt as compared with that of the colloid. An equilibrium is established which, in the case of a few hundred pounds of ammonium salt applied to an acre of land, would result in the reduction of the ammonia remaining in solution to a barely perceptible concentration. Only by the use of solutions of considerable concentration repeatedly applied to a limited quantity of soil can the colloid bases be wholly replaced by the base of the salt in solution. In such a case also, when the salt is in excess of the soil colloid, the hydrogen-ions can be exchanged with the formation of free acid in the solution. Other conditions being equal, hydrogen-ions in the solution are most effective in replacing the other basic ions in the colloid ; potassium is more powerful than ammonium and ammonium than sodium, i.e., a solution of potassium chloride will turn out more bases and give up more of its own base to the absorbing complex than will a corresponding solution of sodium chloride. The bivalent bases, calcium and magnesium, are more effective in replacement than the univalent bases, potassium, sodium, and ammonium.

The base-exchange reactions of the soil are essentially surface reactions. This statement may be qualified in the case of montmorillonite, where reactions may occur within the relatively widely spaced crystal layers: such surfaces may be regarded as inner surfaces. The surface of a particle of the clay-humus complex is formed of anionic groups, principally silicic acid and humic acid groups. Surrounding this shell is a corresponding layer of cations. Represented in its most diagrammatic form, the position is as follows:



where — signifies the negative anions and + the cations, Ca, Mg, K, Na, NH_4, and H. In a moist soil or in aqueous suspension a proportion of these cations will be dissociated from their corresponding anions.

The following are typical base-exchange reactions, represented in the form of chemical equations:

$$\text{Soil} - \text{Ca} + 2\text{NaCl} = \text{Soil} - \text{Na}_2 + \text{CaCl}_2$$

Calcium soil + sodium chloride
= Sodium soil + calcium chloride.

$$\text{Soil} - \text{H} + \text{NaCl} = \text{Soil} - \text{Na} + \text{HCl}$$

Hydrogen soil + sodium chloride
= Sodium soil + hydrochloric acid.

$$\text{Soil} - \text{Ca} + 2\text{HCl} = \text{Soil} - \text{H}_2 + \text{CaCl}_2$$

Calcium soil + hydrochloric acid
= Hydrogen soil + calcium chloride.

In ordinary soils a mixture of exchangeable cations is present. Many methods have been proposed for the determination of the amount of the different cations present. These methods depend on repeatedly leaching the soil with dilute solutions of neutral salts or weak solutions of acids. For example, in the method of Hissink, 25 g. of soil are leached with normal sodium chloride. Successive half litre portions of the leachate are collected and analysed for calcium, potassium, and magnesium. If sodium is required, the leaching must be carried out with ammonium chloride. Most of the exchangeable bases are removed by the first litre of leachings, only small amounts coming out in subsequent leaching.

A more convenient method is to leach the soil with semi-normal acetic acid. All the exchangeable bases can then be determined in the leachate. The determination of exchangeable hydrogen presents difficulties as hydrogen is very firmly held. Barium chloride may be used as a leaching agent, or the amount may be determined by an indirect method.

In the next table the exchangeable base contents of certain typical groups of soils are shown. It will be noticed that, except in the case of alkaline soils, where sodium is the major cation, calcium predominates. Usually, about 75 to 80 per cent. of the total reaction value of the four principal cations is in the form of calcium.

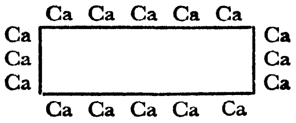
EXCHANGEABLE BASES IN TYPICAL GROUPS OF SOIL.

Soils.	Per cent.			
	CaO.	MgO.	K_2O.	Na_2O.
25 Dutch Clay Soils . .	0·84	0·10	0·04	0·08
17 Scottish Soils . . .	0·28	0·02	0·01	0·01
7 Neutral Soils, U.S.A. .	0·39	0·10	0·04	0·05
5 Alkaline Soils, U.S.A. .	0·0	0·02	0·08	0·21
6 Acid Soils, U.S.A. . .	0·03	0·02	0·01	0·02

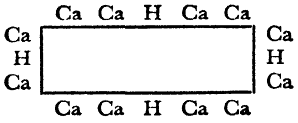
Base-exchange and Soil Acidity

When hydrogen is the only exchangeable cation present, we have what may be termed a hydrogen soil. Such a soil is said to be *base-desaturated.* In humid climates, such as our own, where soils are continually undergoing washing by rainwater charged with carbon dioxide and, to a less extent humic acids, calcium and the other exchangeable bases are lost from the soil and their places in the exchange complex are taken by hydrogen. Let us suppose that we start with a soil containing an excess of calcium carbonate and that this calcium carbonate is in a fine state of division and the soil has reached a state of equilibrium with it. As the soil is leached by rainwater, the calcium carbonate is slowly removed from the soil in the form of calcium hydrogen-carbonate. Analyses of drainage waters at Rothamsted suggest that under English conditions the loss of calcium carbonate from soils containing an excess of this constituent is something of the order of 1,000 lbs. per acre per annum. So long as any excess of calcium carbonate remains in the soil, the soil is said to be *base-saturated.* When it is entirely removed the losses begin to fall on the exchangeable calcium, and to a lesser degree on the other exchangeable bases present, their place being taken by exchangeable hydrogen. The soil now begins to be *base-unsaturated.* With progressive removal of calcium and other bases, and replacement by hydrogen, the soil becomes more and more unsaturated, until finally it becomes *base-desaturated.* In practice this point is hardly reached, because the rate of loss slows down as the soil becomes more unsaturated, and there may be some compensation through liberation of bases from the weathering of minerals present in the soil. This progressive desaturation may be represented diagrammatically, neglecting the minor exchangeable bases, as follows :

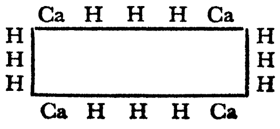
I.



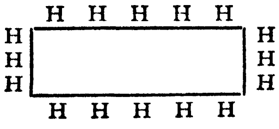
II.



III.



IV.



The degree of acidity of a soil is reflected in the hydrogen-ion concentration of its aqueous suspensions. A dilute aqueous solution of an acid is distinguished by the presence of hydrogen-ions arising from the electrolytic dissociation of the acid. The so-called strong acids, such as hydrochloric acid, are almost completely dissociated in dilute solution, whilst weak acids, such as acetic, are only slightly dissociated. The hydrogen-ion concentration of a solution of an acid thus depends on its concentration and on its degree of dissociation. An unsaturated soil in the presence of water behaves as a weak acid and dissociates hydrogen-ions. The hydrogen-ion concentration of an aqueous soil suspension is thus an index of the intensity of its acidity. This is commonly expressed by its *p*H, which is the negative logarithm of the hydrogen-ion concentration. Thus, if a soil suspension has a *p*H of 6·0, its hydrogen-ion concentration is 10^{-6}, or one-millionth of a gram per litre. The following may be taken as standards:

Extremely acid	less than *p*H 4·0
Acid	*p*H 4·0–5·0
Moderately acid	,, 5·0–6·0
Slightly acid	,, 6·0–7·0
Slightly alkaline	,, 7·0–7·5
Moderately alkaline	,, 7·5–8·0
Alkaline	,, 8·0–9·0
Extremely alkaline	over *p*H 9·0

*p*H values of less than 4·0 usually indicate the presence of mineral acids, such as sulphuric acid, whilst *p*H values above 8·5 are generally a sign of the presence of sodium carbonate.

There is a close relationship between the *p*H of a soil and its content of exchangeable bases. This relationship can be most easily studied by considering the content of exchangeable calcium in relationship to the *p*H of the soil. If we examine a number of soils of the same general type and plot the *p*H against the content of exchangeable calcium, we get an approximately linear relationship. For medium loams with about 6 to 8 per cent. organic matter, the line might be approximately represented by A in Fig. 16A. From it we see that an increase of 0·1 per cent. in exchangeable CaO is accompanied by a rise of about 0·5 in *p*H. With lighter soils, i.e. soils containing smaller amounts of colloidal matter, the *p*H–exchangeable CaO line, B, is steeper, which means that an increase of 0·1 per cent. in exchangeable CaO causes a bigger rise in *p*H than in the case of the medium soils. With clay soils and peat soils the effect of exchangeable CaO on *p*H is less, as is seen from lines C and D in the diagram. The clay soils and peat soils are said to be more strongly *buffered* than the lighter soils. The buffer effect of a soil is thus the resistance that it opposes to changes in *p*H on addition of acids or bases. In practice, this property is of great importance for it tends to maintain a stable reaction in the soil.

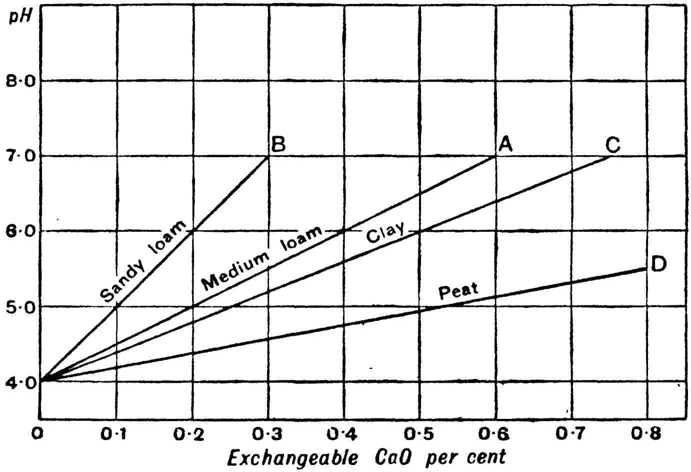


FIG. 16A.—Relationship between *p*H and Exchangeable CaO.

Reference is often made in soil literature to the *base-exchange capacity* of soils. There is no generally accepted definition, but there are numerous methods for its determination, each involving its own definition. A convenient definition, however, is the exchangeable base content, expressed as milligram equivalents, when the soil is exactly neutral, i.e. at *p*H 7·0. A method of determining it is to add increasing amounts of standard barium hydroxide solution to equal amounts of the soils and after standing for some time in order that equilibrium shall be reached, to determine the pH in each case. The pH is then plotted against baryta added and by interpolation the amount required to give pH 7·0 is found. This amount, expressed as milligram equivalents[1] and added to the milligram equivalents of exchangeable bases originally present, gives the base exchange capacity. An alternative method is to leach the soil with neutral barium chloride to obtain the barium soil, and then after washing away the excess of barium chloride, to determine the amount of exchangeable barium in the soil.

If the base exchange capacity of a soil is T milligram equivalents and the exchangeable bases content is S, then the percentage base saturation is $100 \cdot S/T$.

Hydrogen Soils

When a soil is highly unsaturated, i.e. when it is predominantly a hydrogen soil, the colloidal complex becomes unstable. The clay undergoes a partial decomposition, whereby silicic acid and hydrated sesquioxides are liberated. If conditions are extremely acid, particularly if much acid humus is present, the sesquioxides, together with small amounts of humus are washed down from the surface layers and deposited in the subsoil horizons. A marked differentiation thus develops, resulting in a bleached surface horizon and a lower horizon enriched in sesquioxides and showing a rusty or orange colour from the presence of hydrated ferric oxide. At the top of this horizon and separating it from the bleached horizon there may be a thin horizon of humus deposition, often somewhat indurated. The profile thus developed is known as a podsol and is formed in cool humid climates under coniferous or heath vegetation. (Cf. p. 29.)

Sodium Soils

Under certain conditions, sodium salts, principally chloride and sulphate, may be present in the soil profile or in the ground-water. Such conditions do not occur in Britain, except to some extent where land is flooded by sea water. They are commoner in dry climates, where the rainfall is insufficient to remove soluble sodium salts from the soil. The effect of an excess of sodium salts is to change it from a predominantly calcium to a predominantly sodium soil. The excess of salt is, of course, injurious to the growth of crops. Such soils are known as saline soils. In the United States they are known as white alkali soils, from the white efflorescence of sodium salts seen at the surface when they dry out.

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[1] One milligram equivalent is the equivalent weight of a substance in milligrams. Thus, the equivalent weight of CaO is 28 and 1m.E=0·028g.

When saline soils lose their excess of salts, a change occurs. The sodium soil, i.e. the sodium colloid, undergoes hydrolysis. This reaction may be represented by the equation,

$$\mathrm{Na} - \mathrm{Soil} + \mathrm{H_2O} = \mathrm{H} - \mathrm{Soil} + \mathrm{NaOH}$$

The sodium hydroxide takes up carbon dioxide from the soil air and is changed into sodium carbonate. The reaction of the soil now becomes strongly alkaline and the soil loses its granular or crumb structure, so that it becomes compact and impermeable to water movements. With this loss in structure there is a decrease in pore space with the result that the " alkali spot " is marked by a depression in the micro-relief. Here, in wet weather, water accumulates as a shallow pool, and, being alkaline, dissolve shumus from the soil, giving a dark-coloured solution. On drying out the humic material is deposited as a dark varnish on the surface. Such soils are termed *alkaline soils*, or, in the United States, " *black alkali* " soils, from the dark appearance of their surface in drought and to distinguish them from white alkali soils. They are highly infertile, both on account of their alkaline reaction and their bad physical condition. If calcium carbonate is present, the hydrogen soil formed by hydrolysis reacts with it yielding the calcium soil. Alternatively, the transformation may be direct from sodium to calcium soil.

In the absence of calcium carbonate, alkali soils gradually lose their sodium carbonate by slow leaching; the hydrogen soil then undergoes decomposition similar to that which takes place in podsolization, and a profile develops with a bleached surface horizon underlain by a sesquioxidic subsurface horizon. Such a soil is known as a *degraded alkali soil* or a *soloti soil.*

Anionic Exchange

Although less studied than base exchange, anionic exchange can also take place to some extent in the colloidal complex. Silicic acid and humus can be brought into solution by reaction with solutions containing certain anions such as citrate, tartrate, oxalate, and above all, hydroxyl. It is doubtful if these reactions can proceed to completion, certainly not in the case of silicic acid groups of the complex, only a proportion of the external groups apparently being exchangeable. Phosphate ions can be absorbed and replaced from the colloidal complex. Since an appreciable proportion of the phosphorus of certain soils appears to be present in anionic-exchangeable form, an understanding of these reactions is of the greatest interest and importance. At present, however, they have not been fully investigated.

Soil Phosphorus

Soils contain varying proportions of phosphorus. In any given soil, a considerable proportion of the total phosphorus is relatively unavailable to plants. Phosphorus compounds of differing degrees of availability are present and no hard and fast line can be drawn between available and unavailable phosphorus. There is a tendency for phosphorus compounds to be concentrated in the upper horizons of agricultural soils, the figures for phosphoric oxide, P_2O_5, generally running parallel with the organic matter figures. For British soils, total P_2O_5 is generally between 0·05 and 0·25 per cent. The following approximate standards may be given :

Very low	below 0·05 per cent.
Low	0·05–0·10 ,, ,,
Medium	0·10–0·25 ,, ,,
High	above 0·25 ,, ,,

Much lower figures for total phosphoric oxide are found in the soils of many countries overseas, particularly South

Africa and Australia. There is some evidence that high phosphorus figures are correlated with long-continued agricultural use. The sites of ancient settlements are often marked by relatively high phosphorus contents in the soil, even after the settlements have been abandoned.

No satisfactory fractionation of soil phosphorus has yet been made, but it may be assumed that the following categories of soil phosphorus are present :

1. Apatite and apatite-like minerals. The general formula is $Ca_{10}(PO_4)_6X_2$, where X_2 may be $-F_2$, $-CO_3$, or $-(OH)_2$.

2. Di-calcium phosphate, $CaHPO_4$, formed by reaction of soluble phosphate with calcium compounds in the soil. This compound is probably unstable in the soil and reverts to less available forms.

3. Ferric and aluminium phosphates. These compounds are present in acid soils, but are unstable in neutral and alkaline soils, where they react with calcium carbonate to give apatite-like compounds.

4. Phosphoric acid groups in the colloidal complex. These are probably of low availability to plants.

5. Phosphoric acid groups in humus. These also are probably of low availability.

6. Organic phosphorus compounds such as nuclein and lecithin in undecomposed plant and animal residues.

Unfortunately, no trustworthy methods are yet available for determining the distribution of phosphorus between these categories. There is some evidence that apatite phosphorus is a dominant fraction in neutral and alkaline soils, whilst in acid soils, ferric and aluminium phosphates are the more stable forms. When an acid soil is limed, one of the results is that ferric and aluminium phosphates are decomposed, with formation of phosphates of the apatite group. There may also be some liberation of phosphate from organic forms as a consequence of increased biological oxidation.

Absorption of Phosphoric Acid

The retention of dissolved phosphoric acid and phosphates cannot be explained in exactly the same way as the retention of potassium and ammonium salts, because the phosphoric acid is not a cation which can be exchanged for the bases in the colloids. None the less, the same colloidal constituents have the property of withdrawing phosphates from solution. The phosphoric acid enters the anion nucleus of the colloid in some sort of loose partnership, retained there by the cations in the shell. The anions of the commoner salts will not be attracted by the colloid complex, for example, nitrate, chloride and sulphate ions are not retained but leach freely through an ordinary soil. That the colloids function in the adsorption of phosphoric acid may be deduced from the reverse action seen when the soil is brought into contact with weak acid solution. Russell has shown that this action can best be explained by assuming a preliminary complete solution of all the phosphoric acid present in a form capable of solution followed by a back reaction in which the phosphoric acid is reabsorbed to an extent determined by the nature and strength of the dilute acid with which the soil is in contact.

Phosphoric acid in solution also enters into slow combination with other materials in the soil, e.g. with calcium carbonate and hydrated ferric oxide, with the production of more or less gelatinous precipitates, susceptible of solution in the soil water containing carbon dioxide. Of these the ferric phosphates rapidly become more insoluble; for example, soils are known derived from the marlstone of the Middle Lias which on analysis are exceptionally rich in phosphoric acid but behave as though that element was deficient, in that they give a marked response to manuring with superphosphate.

In an ordinary soil containing a sufficiency of calcium carbonate, the application of a soluble phosphate like superphosphate will chiefly result in the precipitation of di-calcium or " reverted " phosphate, wherever the solution meets with a particle of calcium carbonate. This di-calcium phosphate is a compound easily soluble in weak organic acids or in water containing carbonic acid : hence the great value of applications of superphosphate on soils rich in lime, for thus a readily available phosphate is very quickly disseminated throughout the ground in a state of fine division. But on soils poor in calcium carbonate the precipitation will be to some extent effected by the hydrated iron and aluminium compounds ; the resulting phosphates are practically insoluble in water containing carbonic acid, and but little in saline solutions or in weak organic acids. Hence applications of superphosphate to such soils become much less available to the crop, and should be preceded by a thorough liming of the land. Even a subsequent liming on soils containing phosphates of iron or alumina will help to bring them into a more available form, because a double decomposition resulting in calcium phosphate and aluminium or ferric hydrate will proceed to an extent dependent on the mass of lime present in the medium. It is possible that in markedly alkaline soils calcium compounds of low availability may be formed.

Evidence of the precipitation of phosphoric acid within the soil is afforded by Dyer's examination of the Rothamsted wheat soils at various depths, after fifty years' continuous manuring with and without superphosphate. By comparing the amount of phosphoric acid contained in the soil of the unmanured plot with that contained in the soils of the plots receiving superphosphate every year, and knowing also the amount removed by the successive crops in each case, it is possible to calculate the surplus that should remain in the manured over the unmanured plots, on the assumption that the soil was uniform at starting. Calculating in this way, Dyer found no less than 83 per cent. of the phosphoric acid which six of the plots should possess after fifty years' manuring was still present in the top 9 inches of soil, whereas the subsoils from 9 inches to 18 inches, and 18 inches to 27 inches, showed no accumulation of phosphates. Dyer further determined the phosphoric acid soluble in a 1 per cent. solution of citric acid, and found that on the manured plots the top 9 inches of soil contained about 39 per cent. of the estimated surplus of phosphoric acid so combined as to be soluble in this medium, whereas in the subsoils the "available" phosphoric acid was, if anything, less for the manured than for the unmanured plots.

Dressings of superphosphate applied on the surface of arable soils are retained within the top few inches, whilst grass plots that have received repeated dressings of basic slag show a high concentration of phosphoric oxide in the turf layer. Further evidence of the absorption of phosphate by soils is the almost complete absence of phosphate from drainage waters.

It may be helpful to distinguish between phosphate absorption and phosphate fixation, restricting the latter term to those types of absorption in which phosphorus compounds of low availability to plants are formed. Phosphate fixation would thus comprise the following processes: (1) Formation of relatively unavailable phosphates of iron and aluminium by precipitation in acid soils; (2) formation of relatively unavailable calcium phosphates by precipitation in alkaline soils; (3) absorption of phosphate by the colloidal complex in the soil; and (4) conversion of phosphate by micro-organisms into unavailable organic phosphorus compounds.

The problem of phosphorus fixation is of great importance for practice. The recovery of phosphate added in fertilizers rarely exceeds 20 per cent. In view of the limited world supplies of phosphate, phosphorus may at some later date become a limiting factor in world food supply. It is therefore necessary to study how to secure the most economical use of the available supplies. At present the most promising solution appears to be the placement of the fertilizer, either by drilling with the seed, or by laying it in a band in the vicinity of the seed rows, using a special type of fertilizer drill.

Accessory Soil Constituents

By accessory constituents are understood compounds of frequent, but not invariable, occurrence in the soil. For example, although many soils contain calcium carbonate it is not an essential constituent of all soils, in the same way that organic matter and clay are essential, for many of the world soil groups are actually characterized by the absence of calcium carbonate in the soil horizons. Accessory constituents are of importance because of the light they throw on conditions within the soil and their significance in soil classification.

Calcium Carbonate.—As indicated above, calcium carbonate is a common, but not an essential constituent of soils. In humid climates such as that of Britain, calcium carbonate is continually being leached out from the soil profile into the drainage in the form of calcium hydrogen-carbonate. In the absence of any compensatory process, therefore, all British soil would eventually become completely deprived of calcium carbonate. Even soils lying over limestone are frequently carbonate-free. On the other hand, there are large areas of soil over chalk that contain large proportions of calcium carbonate. These might possibly after many centuries become carbonate-free in their upper horizons ; but it is possible that denudation may be sufficiently rapid to maintain a certain content of calcium carbonate in arable land. Under permanent grass, with protection from erosion, doubtless a carbonate-free horizon would develop at the surface, as is actually the case in some of the soils of the chalk downs that have never been under cultivation. Soils developed from calcareous parent materials in poorly drained situations, with lime-rich ground-water may also maintain a content of calcium carbonate. Apart from such cases, the presence of free calcium carbonate in British soils is generally due to previous additions of liming materials. The amount of calcium carbonate originating in this way is often considerable. At Rothamsted, where up to 100 tons per acre of chalk have been spread in past generations, many of the fields still contain 4 or 5 per cent. of calcium carbonate. In some North Welsh soils over 10 per cent. of calcium carbonate has been found, arising from the liming of former generations of farmers.

Calcium carbonate as a permanent constituent of the soil is found in soils developed under arid climates. Here the calcium carbonate is deposited at a depth below the surface, corresponding with the depth to which leaching is effective. In the tshernosems or black earths, the carbonate zone may occur at 2 to 3 feet. Passing to the soils of still drier climates, the zone of carbonate accumulation becomes more pronounced and approaches nearer to the surface, so that in certain desert soils it may actually occur at the surface, if the top soil has been removed by erosion.

Calcium carbonate may occur in the zone of a fluctuating water-table in all parts of the world if the parent material is calcareous or if the ground-waters are rich in lime.

Gypsum.—The occurrence of gypsum in the soil, although less common than that of calcium carbonate, is governed by similar conditions. In Britain, it is found only in certain soils with impeded drainage, as, for example, in some soils derived from Kimmeridge Clay. The parent material contains iron pyrites, which becomes oxidized during weathering, yielding hydrated ferric oxide and sulphuric acid. By reaction with calcium carbonate, gypsum is formed, which occurs as easily recognizable crystals in the vicinity of the weathering zone. Where drainage is free, any gypsum thus formed is washed down into the drainage and lost from the soil horizons.

In tshernosems and similar soils, gypsum may occur as a distinct horizon below the calcium carbonate horizon.

Manganese Dioxide.—This compound occurs in many soils in the form of small specks, patches, or even concretions. Its occurrence is usually associated with defective drainage conditions. An excavation in a poorly drained soil will often show black streaks along the sides where the spade has cut through soft aggregates of manganese dioxide. Manganese dioxide may also occur in a less localized distribution and finer state of division, particularly in certain red tropical soils.

The Composition of Drainage Waters

Evidence of the fate of the various substances applied as manures, and their retention or otherwise by the soil, can be obtained by studying the composition of the water flowing from land drains.

The drainage from the continuously manured wheat plots at Rothamsted, each of which possesses a tile drain running down the centre at a depth of 2 feet to 2 feet 6 inches, has been collected from time to time and completely analysed by Voelcker and Frankland ; in addition, systematic determinations of the nitrogen contents have been made for many years. In a general way, the chief constituent of the various drainage waters is lime, either as bicarbonate, sulphate, chloride, or nitrate ; soda is the only other base present in any quantity ; very small amounts of magnesia, potash, and ammonia pass into the drains. Of the acid radicles, chloride and sulphate predominate, according to the manuring, and the proportion of phosphoric acid is minute ; but the amount of nitrate varies according to the manure applied and the season at which the water is collected.

The table on p. 161 shows the complete analysis of the drainage water from twelve of the plots.

An examination of these figures shows that the amount of organic matter and ammonia reaching the drains is practically nil ; the organic matter supplied as dung, and the ammonia, which is applied up to the rate of 400 lbs. of mixed ammonium chloride and sulphate per acre, are wholly retained by the soil. The effect, however, of adding either organic compounds of nitrogen or ammonium salts is to increase the proportion of nitrates in the drainage water. Lime is the chief constituent of the dissolved matter in the drainage waters, the proportion is lowest for the unmanured plot 3, it rises with the application of minerals (5), and rises again with each successive application of ammonium salts in plots 6 and 7. The formation of calcium chloride and sulphate respectively, when the corresponding ammonium salts are applied to land containing calcium carbonate, has already been discussed : it is well seen in the increased richness in lime, sulphuric acid, and chlorine of the drainage water from plots 6 and 7, which receive 200 and 400 lbs. respectively of ammonium salts, as compared with plot 5, which receives the same minerals without any nitrogen compounds. Plot 11 receives superphosphate in addition to the ammonium salts which plot 10 receives: the effect of the gypsum contained in the superphosphate is seen in the increased lime and sulphuric acid content of the drainage water of plot 11. The increase is not so great, however, as that caused by the addition of sulphates of potash and magnesia to the superphosphate and ammonium salts (plots 13 and 14) whereas sulphate of soda causes little loss of lime (12). The use of nitrate of soda on plot 9 causes no increase in the proportion of lime in the drainage water, but a large quantity is removed, chiefly as sulphate, from plot 2, receiving dung every year. The quantity of lime removed annually in this way will be very great: assuming a mean annual drainage equal to 10 inches of water, the unmanured plot will lose about 220 lbs. per acre per annum of lime: equivalent to about 400 lbs. of carbonate of lime, whereas the analysis of the soil shows an annual loss of about 800 lbs. per acre. The discrepancy between these two figures is due to the fact that the results are calculated from but a small number of analyses of the drainage water, the amount of which is also very uncertain. When 400 lbs. of ammonium salts are used as manure, either alone or with minerals, the increased loss of lime calculated on the same basis amounts to 126 lbs. or 225 lbs. of carbonate of lime per acre per annum, as against about 240 lbs. found from the analysis of the soil.

The amount of magnesia lost is small, 5 to 20 lbs. per acre per annum, nor is the amount reaching the drainage water much increased by its application as manure to plots 5, 6, 7, 9, and 14 respectively.

The amount of potash lost is still smaller, from 3 to 12 lbs. per acre per annum, but it is distinctly dependent on the amount supplied as manure, being at a maximum with the dunged plot 2 and plot 5, receiving minerals only, and greater from all the other plots receiving potash than from those without it, i.e., plots 3, 10, 11, 12, 14. The use of sulphate or nitrate of soda increases the amount of potash in the drainage water; not so, however, the use of sulphate

COMPOSITION OF DRAINAGE WATERS FROM BROADBALK FIELD, ROTHAMSTED, IN PARTS PER MILLION (VOELCKER)

PLOT.	2	3 & 4	5	6	7	9	10	11	12	13	14
Manuring.	Dung.	0	MINERALS.				400 LBS. AMMONIUM SALTS.				
			0	+200 lbs. Ammonium Salts.	+400 lbs. Ammonium Salts.	+550 lbs. Nitrate of Soda.	0	+Superphosphate.			
								0	+Sulphate of Soda.	+Sulphate of Potash.	+Sulphate of Magnesia.
Organic Matter	26·1	22·9	19·3	25·7	34·9	26·7	33·6	38·4	29·3	45·3	56·1
Nitrogen as Nitric Acid	16·1	3·90	5·10	8·50	14·0	18·4	13·9	15·3	15·1	17·4	19·2
Nitrogen as Ammonia	0·16	0·12	0·13	0·20	0·07	0·24	0·08	0·17	0·30	0·16	0·09
Lime	147·4	98·1	124·3	143·9	181·4	118·1	154·1	165·6	191·6	201·4	226·7
Magnesia	4·9	5·1	6·4	7·9	8·3	5·9	7·4	7·3	6·6	9·3	11·6
Potash	5·4	1·7	5·4	4·4	2·9	4·1	1·9	1·0	2·7	3·3	1·0
Soda	13·7	6·0	11·7	10·7	10·9	56·1	7·1	6·6	24·6	6·1	5·6
Oxide of Iron	2·6	5·7	4·4	2·7	8·1	5·1	4·0	3·4	3·6	3·7	3·7
Chlorine	20·7	10·7	11·1	20·7	26·1	12·0	32·0	31·6	30·9	36·6	39·4
Sulphuric Acid	106·1	24·7	66·3	73·3	90·1	41·0	44·4	54·3	96·7	86·9	99·7
Phosphoric Acid	...	0·63	0·91	1·54	0·91	...	1·44	1·66	1·26	1·09	1·01
Carbonic Acid	43·3	48·1	44·4	59·0	58·0	73·0	45·4	44·9	64·6	51·1	56·9
Silica	35·7	10·9	15·4	24·7	17·0	10·6	10·9	11·3	17·9	28·3	14·0
Total Solids	476·1	246·4	326·0	407·6	492·4	423·9	406·9	425·9	530·9	544·3	598·6

of magnesia. Practically all the soda, chlorine, and nearly all the sulphuric acid, that are applied in the manure pass through into the drainage water.

A comparison of the drainage waters in winter and spring shows that they are more concentrated in the winter, because the manures (excepting the nitrate of soda) have then been recently applied : the chlorides wash out first, then the sulphates, and as the season advances not only is the total amount of lime present much diminished, but it comes away chiefly as bicarbonate. With the growth of the crop in spring the nitrates disappear from the drainage waters.

The amount of nitrates found in the drainage water varies not only with the time of year, but also according to the interaction of temperature, growth of crop, cultivation, and percolation. Nitrates are rapidly produced only when the temperature of the soil has risen : if the percolation is not excessive the crop may remove the nitrates as fast as they are formed, but a heavy rainfall in the spring before the nitrates have been much drawn upon by the crop, or one just after the land has been broken up in the autumn and is still warm, will result in a considerable washing out of nitrates. At the same time a certain amount of moisture in the soil is necessary for the formation of nitrates, and the crop itself may so dry the soil as to reduce nitrification considerably. The following table shows the estimated loss of nitrates from the same wheat plots at Rothamsted as have previously been dealt with, during two years, each of which has been divided into two periods : firstly, from the date at which the nitrogenous manures were sown up to harvest ; and secondly, from harvest round again to the sowing of manures in spring.

The diagram (Fig. 17) shows the same results in a graphic form.

The seaons were rather exceptional, the summer rainfall and drainage in 1879 and the winter rainfall in the following year being both above the average. It will be seen that except on the autumn manured plot 15, the loss was greatest from plot 9, receiving 550 lbs. of nitrate of soda, and this excess of loss was chiefly in the summer drainage water of

1879; the figures are, however, exaggerated by the fact that half the nitrate plot received no mineral manures, and therefore grew but a scanty crop. The losses during the winter months are more nearly the same for all plots, and represent to a large degree the nitrification of the organic residues in the soil. The losses from the plots receiving minerals and varying amounts of ammonium salts (5, 6, and 7) increase with each application of nitrogen: the losses from

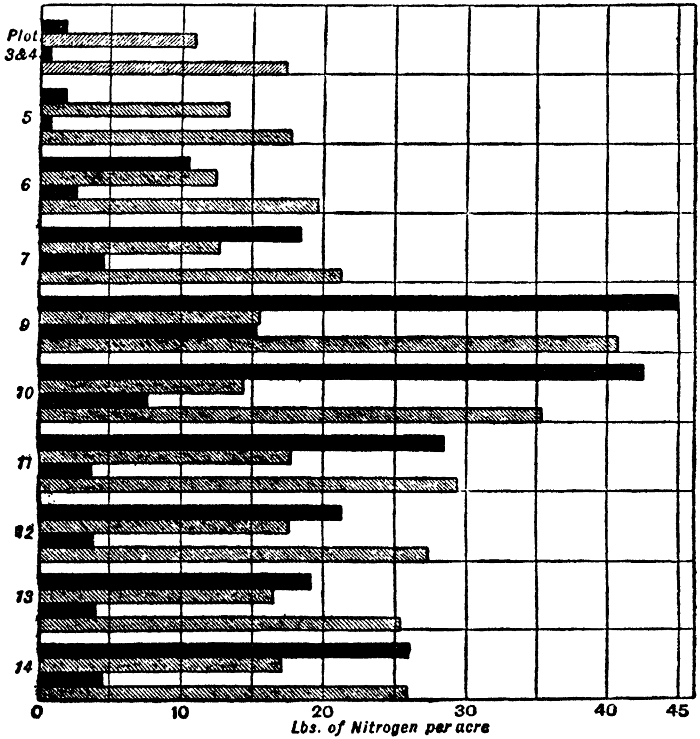

FIG. 17.—Losses of Nitrogen in Drainage from Rothamsted Wheat Plots.

Black = Losses in Summers 1879, 1880.
Shaded = Losses in following Winters.

the plots receiving ammonia and various mineral manures diminish as the mineral manure becomes a more complete plant food, because the greater growth of crop thus secured more completely removes the nitrates as they are formed, besides hindering nitrification by drying the surface soil.

Nitric Nitrogen in Drainage Water—Lbs. per Acre

Plot.	Manuring, per Acre.	1879–80.		1880–81.	
		Spring Sowing to Harvest.	Harvest to Spring Sowing.	Spring Sowing to Harvest.	Harvest to Spring Sowing.
3	Unmanured	1·7	10·8	0·6	17·1
5	Minerals only	1·6	13·3	0·7	17·7
6	Minerals + 200 lbs. Ammonium Salts	10·1	12·6	2·2	19·8
7	„ + 400 „ „	18·3	12·6	4·3	21·4
9	„ + 550 „ Nitrate of Soda	45·0	15·6	15·0	41·0
10	400 lbs. Ammonium Salts alone .	42·9	14·3	7·4	35·2
11	„ „ + Superphosphate	28·3	17·7	3·4	29·6
12	„ „ + Sulph. Soda .	21·2	17·5	3·3	27·2
13	„ „ + Sulph. Potash	19·0	16·4	3·7	25·3
14	„ „ + Sulph. Mag. .	26·0	16·8	4·2	25·9
15	Minerals + 400 lbs. Ammonium Salts in Autumn	9·6	59·9	3·4	74·9
	Estimated Drainage—inches .	1·11	4·7	1·8	18·8

The effect on nitrification of crop and surface cultivation is well seen in the following table of results obtained by Dehérain, who collected the drainage from cement tanks 2m. cube and systematically filled with soil taken from corresponding depths in the field. The soils had been several years in the tanks, so that they had settled down into practically normal conditions, though the effect of the aeration and disturbance of the soil in filling the tanks is still visible in a rather high rate of nitrification. Each tank carried the crop indicated in the first column.

The rainfall of the year in question, March 1896 to March 1897, amounted to 28·8 inches, most of which fell in the autumn. The most noteworthy results are the effect of the various crops in diminishing the loss of nitrates, which is not wholly to be attributed to the quantity taken up by the crop, because the sum of the nitrogen removed in the crop and that carried off in the drainage water is never equal to the nitrogen removed from the uncropped plots by the drainage water alone. During the comparatively dry spring months the crops leave so little moisture in the soil that nitrification is checked, and the total production of nitrates is less where there is a crop than on the moister uncropped plots.

Cropping.	Drainage.	Nitrogen as Nitric Acid.
	Inches.	Lbs. per acre in Drainage Water.
Fallow, no cultivation	11·2	186·70
Rye Grass	7·8	2·28
Oats	7·3	7·37
Maize	6·9	21·60
Wheat, followed by Vetches	6·6	12·90
Wheat	7·5	28·70
Fallow, hoed	11·5	196·56
Fallow, no cultivation	11·2	158·00
Fallow, hoed and rolled	11·2	183·20
Vine	7·5	36·20
Sugar Beet	7·2	0·27

When the wheat was followed by a crop of vetches the loss of nitrates during the comparatively wet autumn was considerably reduced. Lastly, the hoeing of the fallow plots resulted in a considerably increased production of nitrates.

Time of Application of Manures

The facts set out above as to the retention of most of the soluble constituents of manures by the soil, whilst the nitrates are liable to wash out, have an important bearing on the season at which artificial manures should be sown. In the first place it is evident that there is no danger of losing phosphates, or even of their washing deep into the soil, when employed in their most soluble form as superphosphate. It is the general custom to sow superphosphate with the drill for roots at the same time as the seed : the large quantity of manure near the seedling in its early critical stages is probably valuable, and as the roots of swedes and turnips do not extend very deeply, the phosphoric acid may be placed in the most likely place to reach them.

But for more deeply rooting crops, hops and fruit or even mangolds, it seems probable that superphosphate is often applied rather too late in the season, and that if used as a winter instead of a spring dressing it would have a better chance of getting well diffused through the soil. Basic slag and other insoluble phosphates should be used in the winter or even the autumn ; there is no risk of loss, and as much rain as possible is wanted to get them distributed in the soil. As regards potash salts, Dyer's experiments go to show that they descend further in the soil, and are a little more subject to washing than the soluble phosphates : for this reason, where sulphate of potash is employed, as for potatoes, it will best be sown with the seed. Where kainit is used, it is best employed as a winter or autumn dressing ; there will be little loss of potash, for this will get fixed chiefly in the surface soil. But the chlorides, which are present in kainit and are sometimes not wholly beneficial in their action upon the crop, will be removed and washed out into the drains or the subsoil water by the winter rains : the magnesium salts also will be precipitated within the soil, and to a large extent removed from possible action upon the crop. Turning to the nitrogen compounds, it is necessary to keep in mind that all of them will become transformed into nitrates, which are liable to be washed out. All insoluble organic manures should be put on before or during the winter : the decay processes will begin, resulting in the formation of amino-acids, ammonia, etc., which will become fixed in the soil, but the low winter temperatures will not permit of much nitrification. Liquid manure and similar materials containing such readily nitrifiable substances as urea and ammonium carbonate, should be reserved until early spring, so that the crop may be growing whenever nitrification begins. Ammonium salts are very rapidly nitrified, so that they should only be used in spring. At Rothamsted nitrates begin to appear in the drainage water immediately after the application of the ammonium salts to the wheat plots in March if rain falls, and one of the plots which has its ammonium salts applied in autumn shows not only a considerable falling-off in crop but also large quantities of nitrates in the winter drainage waters.

The following table shows the amounts of nitrates removed in the drainage water from the two plots which receive 400 lbs. per acre of ammonium salts with mineral manures, only differing in the fact that on plot 7 the ammonium salts are sown in March, and on plot 15 in October; also the average crops of grain and straw for the twenty-three years, 1875-97.

1879-1881.—Lbs. of Nitric Nitrogen per Acre

Plot.	1879-80.		1880-81.		Crop.	
	Spring Sowing to Harvest.	Harvest to Spring Sowing.	Spring Sowing to Harvest.	Harvest to Spring Sowing.	Grain.	Straw.
					Bushels.	Cwt.
7	18·31	12·63	4·29	21·38	31½	31
15	9·62	59·92	...	74·94	28½	26½
Drainage	11·1″	4·7″	1·8″	18·8″	...	...

That sulphate of ammonia will to some extent persist in the soil and become available for a succeeding crop, after even a whole year has elapsed, is to be seen from the results of the Woburn experiments upon wheat. Some of the plots at Woburn receive mineral manures every year, but ammonium salts or nitrate of soda only every alternate year: in both cases the crop falls very much in the years of no nitrogen, but the decrease is by no means so marked with ammonium salts as with nitrate of soda, which latter seems to leave no residue whatever.

The soil at Woburn is an open sandy loam ; but in the years for which the results are quoted the rainfall was low—

Plot.	1899.	Bushels.	1900.	Bushels.
8B	Minerals only	20·3	Minerals + Ammonium Salts	27·3
8A	Minerals + Ammonium Salts	33·1	Minerals only	16·2
9B	Minerals only	9·8	Minerals + Nitrate of Soda	27·7
9A	Minerals + Nitrate of Soda	41	Minerals only	6·8
4	Minerals only, every year	6·9	Minerals only	5·9

The difference between the results set out in the above table and those obtained upon the corresponding plot at Rothamsted, where the dressing of ammonium salts every other year seems to leave no residue for the following year, may perhaps be set down to the different texture of the two soils. The ammonium salts are converted into nitrates, which are washed down into the subsoil ; at Woburn they can rise again by capillarity, as the soil, though sandy, is still fine in texture ; at Rothamsted the soil is too close-grained to admit of any considerable movement of the subsoil water back to the surface.

The experiments recorded above and the results of the examination of drainage waters go to show that nitrate of soda should only be employed when there is a crop in possession of the ground and ready to seize upon the salt as soon as it becomes diffused through the soil. Only on dry soils can it be safely applied as early as the sowing of the seed ; in wet climates sulphate of ammonia will often be preferable if the soil is warm enough to induce reasonably quick nitrification, and when large quantities of nitrate are wanted they should be put on by successive applications of not more than 1 cwt. per acre at a time.

CHAPTER VIII

THE LIVING ORGANISMS OF THE SOIL

Decay and Humification of Organic Matter in the Soil—Changes of Organic Matter in the Soil—The Fixation or Free Nitrogen by Bacteria living in Symbiosis with Leguminous Plants—Soil Inoculation with Nodule Organisms—Fixation of Nitrogen by Bacteria living free in the Soil—Nitrification—Denitrification—Nitrogen Cycle in Nature—Iron Bacteria—Sulphur Bacteria—Fungi of Importance in the Soil: Mycorhiza; "Finger-and-Toe."

THE soil is the seat of a number of slow chemical changes affecting the organic material it receives: residues of an animal or vegetable nature, when applied to the soil, are converted into the dark-coloured complex known as "humus," which becomes slowly oxidized to carbonic acid, water, nitric acid, and other simple substances serving as food for plants. These changes, at one time regarded as purely chemical, are now recognized as dependent upon the vital processes of certain minute organisms, universally distributed throughout cultivated soil, and subject to the same laws of nutrition, multiplication, life, and death, as hold for the higher organisms with which we are more generally familiar.

The microscopic life of the soil, roughly classed as protozoa, fungi, algæ, and bacteria, is vast, and has been very inadequately explored as yet: certain types of change in the soil materials have, however, been associated with particular organisms or groups of organisms, and many of these changes are of fundamental importance in the ordinary nutrition of plants. The organisms in the soil which so far have received the chief attention are those concerned with the supply of nitrogen to the plant. Certain organic compounds of nitrogen, chiefly of a protein nature, become gradually broken down by the action of soil bacteria into simpler compounds, e.g., into amino-acids, and then into ammonia, which latter substance is seized upon by other organisms and oxidized successively to nitrous and nitric acid. As nitrates are generally the form in which the higher plants obtain the nitrogen they require, the fertility of the soil is wholly bound up in the maintenance of this cycle of change. Under certain conditions the work of other organisms intervenes, and the nitrogen compounds, instead of becoming nitric acid, are converted into free nitrogen gas, and are lost to the soil. On the other hand, another group of organisms possesses the power of " fixing " free nitrogen, i.e., of taking the gaseous element nitrogen and combining it with carbon, hydrogen, oxygen, etc., into forms available for the higher plants. Such organisms sometimes act when living in " symbiosis " with plants possessing green carbon-assimilating tissue : the two form a kind of association for mutual support, the bacteria deriving the carbohydrate which they must consume from the higher plant supplied by them with combined nitrogen.

Other symbiotic processes have been traced in the soil, and may yet be made to play an important part in the nutrition of field crops. Indeed, a number of tentative trials have already been made with the view of increasing the productiveness of the soil by introducing either useful organisms that were wanting, or improved types to replace already existing kinds of less effective character.

The Changes of Organic Matter in the Soil

The surface layer of soil is constantly receiving additions of organic matter, either leaves and other débris of vegetation covering the ground, together with the droppings of animals consuming that vegetation, or dung and other animal and vegetable residues supplied as manures to cultivated land. These materials rapidly change in ordinary soil, losing almost immediately any structure they possess, becoming dark-coloured humic bodies, or even burning away as thoroughly as if placed in a furnace. That these changes are due to micro-organisms is seen by their immediate cessation if the soil be treated with antiseptics like chloroform or mercuric chloride : or if the mixture of soil and organic matter be sterilized by heating. Attempts have been made to estimate the number of bacteria contained in the soil : the prodigious numbers obtained, up to thousands of millions per cubic centimetre of the upper soil, show little beyond the fact that the soil is tenanted much as any other decaying organic material would be. The soil bacteria are always associated with a certain number of fungi and yeasts, especially when the reaction of the medium is at all acid : the organisms are most numerous in the surface layer, though they are still to be found in the deepest subsoils. Below a certain depth they must disappear, because deep well-water often comes to the surface in an absolutely sterile condition. The changes which organic materials undergo in the soil may be roughly grouped into two classes ; according as there is free access of oxygen or not, either oxidation with eventual formation of carbon dioxide, water, and, in the case of nitrogenous compounds, nitrates or ammonia, or " humification " will set in. These changes can be illustrated by the fate of a dead branch when it falls either upon the ground, or into a pond or swamp where it becomes buried in the mud at the bottom. In the latter case the fermentation changes cause the wood to darken even to blackness ; gases like carbonic acid and marsh gas are split off so that the material becomes proportionately richer in carbon and poorer in oxygen. Eventually, however, the process slackens, the losses practically cease, and a large proportion of the original material persists. On the other hand, the branch exposed to the air, without darkening very much, becomes slowly resolved by the action of fungi and bacteria into carbonic acid and water, ammonia, nitrogen gas, and mineral salts, with much the same final result as though it had been placed in a furnace. In soil, both these types of change may go on, and the conditions of the soil as regards aeration, drainage, temperature, and cultivation, determine which will predominate.

Practically, the whole group of aerobic bacteria, i.e., those which require free oxygen for their development, and fungi are capable of bringing about the oxidative changes which result in the production of carbon dioxide, the combustion of some carbohydrate being essentially the means by which they derive their energy. As an intermediate step between the carbohydrate and the carbon dioxide, a certain amount of humus is produced—" mould " or the " mild humus " of the

German writers. Examples of this material can be seen in the leaf-mould collected by gardeners from woods, or the fine, brown powder which can be scraped out of the inside of a hollow tree, particularly of a willow; this mould differs from the peaty humus, to be described later, in its neutral reaction and in the readiness with which it can be further oxidized. Neutral in its reaction, it yields but little soluble "humic acid" to the attack of an alkali.

Besides carbohydrates, most aerobic bacteria require some carbon compound of nitrogen, and will begin to break down protein and other nitrogen-containing materials. The products of their attack are successively peptones, bodies like leucine and tyrosine, eventually ammonia, and sometimes free nitrogen, but the ultimate production of ammonia is perhaps the most characteristic feature of the aerobic fermentation of protein bodies. Amides are also resolved into ammonia, of which a characteristic example is afforded by the change of urea into ammonium carbonate. This process, which is one of hydrolysis, not of oxidation, being represented in the gross by the equation

$$CO(NH_2)_2 + 2H_2O = (NH_4)_2CO_3$$

is brought about by more than one organism, universally distributed and abundant in such places as stables and cattle stalls. In warm weather the conversion of the urea of the urine into ammonium carbonate is very rapid, and as the resulting product dissociates into gaseous ammonia and carbonic acid, to this cause is due the smell of ammonia which is always to be noticed in such places. These changes to ammonia are the necessary preliminaries to the final oxidation process or nitrification, which, as the means by which the higher plants receive their supplies of nitrogen, will be discussed separately. The various oxidation processes in the soil are, like all other bacterial actions, promoted by a certain warmth, the optimum temperature being about 25°–30°, by a sufficiency of moisture, and by the presence of mineral food, like phosphates and potash salts In any great quantity, however, salts are harmful, particularly sodium chloride; an acid reaction also diminishes considerably the rate of decay. Speaking generally, bacteria do not thrive when the reaction of the medium is much below the neutral point, and the decay processes are carried out chiefly by the development of fungi when the medium is acid.

In the soil of certain of the Rothamsted grass plots that have become acid through the long-continued application of ammonium salts, bacterial actions are very much reduced or even brought to a standstill; the bacteria of nitrification, for example, are absent. The decay of the grass roots and stubble is brought about by microscopic fungi which abound, and proceeds to such a slight extent that a layer of raw humus has formed on the surface. The formation of raw humus must always be associated with this acid reaction of the surface soil. In this way we may account for the fact that tree-remains are generally found at the bottom of any peat bog and that evidence of forest growth is apparent on the soil surface of places like the Welsh hills or Dartmoor, now covered with a thin peaty vegetation but where no indigenous trees grow. When the soil first became clothed with vegetation after the glacial epoch a forest developed, but as the soil became acid through the accumulation of organic residues and its initial lack of carbonate of lime the trees died, and can only be replaced by others which are tolerant of acid conditions. The presence of chalk, or any form of carbonate of lime, by neutralizing any acids as fast as they are formed, promotes the destruction of organic matter. Wollny has also shown that calcium humate will oxidize much more rapidly than uncombined humic acid placed under similar conditions. Portions of the acid grass plots at Rothamsted have been limed, whereupon the peaty surface accumulation rapidly disappears. To the absence of carbonate of lime and mineral salts generally, may be ascribed the tendency of humus to accumulate and persist on the very light, sandy heaths, where the soil is dry and hot in summer, and also well aerated. It has already been indicated, in treating of humus, that the various organic compounds of nitrogen show very different susceptibility to the breaking-down process which eventually renders the nitrogen available for the crop—amongst the most resistant substances being the nucleo-proteins in the undigested portions of food which form dung, and the humus residues from poor, cropped-out land.

Anaerobic decomposition, which goes on in absence of oxygen, is brought about by a large number of bacteria, some of which are only active in the absence of oxygen, others are aerobic, but will continue their work when deprived of free oxygen. Carbohydrates are decomposed with formation of carbonic acid and other gases like hydrogen and marsh gas, butyric, and other fatty acids, a residue of humus being always produced at the same time. The protein bodies readily undergo putrefactive change, with the production of tyrosine and various amino-acids, fatty acids, ammonia, phenol, and other bodies containing an aromatic nucleus, gaseous compounds of sulphur, etc. In the main, however, the anaerobic changes of organic material in the soil fall upon the cellulose and other fibrous constituents; they lose carbonic acid, marsh gas, hydrogen, etc., and become humus with a gradually increasing proportion of carbon; the nitrogenous materials resist attack more than the carbohydrates, and hence tend to accumulate, so that an old sample of deep-seated peat is richer in nitrogen than a more recent sample taken from nearer the surface. Finally, the humus thus produced, which may be called peat, is essentially an acid product, and even when aerated and supplied with mineral materials will oxidize with extreme slowness.

The Fixation of Free Nitrogen

In the earliest theories regarding the nutrition of the plant which were accepted after chemistry had become an exact science, it was considered that the plant derived its nitrogen from the humus of the soil, as, for example, in de Saussure's statement that " Plants receive their nitrogen almost entirely by the absorption of the soluble organic substances." This view was displaced by the so-called " mineral theory " of

Liebig, who, in laying down the broad principle that the plant only derived certain necessary mineral constituents, its " ash," from the soil, but the whole of its carbon compounds from the atmosphere, was led to regard the nitrogen as well as the other combustible matters of the plant as due to the atmosphere, largely because of the exaggerated estimate which then prevailed as to the amount of ammonia from the air that was brought down in the rain. Boussingault had already shown, by weighing and analysing the crops on his own farm for six separate courses of rotation, that from one-third to one-half more nitrogen was removed in the produce than was supplied in the manure. The gain of nitrogen was little or nothing when cereal crops only were grown, but became large when leguminous crops were introduced into the rotation. Liebig, however, considered that cereals, as well as the other plants, were able to draw their ammonia from the atmosphere, and that, provided sufficient mineral plant food were forthcoming, there was no need of ammonia compounds in the manure.

This view of Liebig's, though modified later, when he admitted that cereals must obtain their nitrogen from a manurial source in the soil, led to considerable investigation of the source of the nitrogen in the plant. Boussingault himself carried out a long series of laboratory experiments, in which weighed seeds containing a known proportion of nitrogen were grown in artificial soils containing no nitrogen, but supplied with the ash constituents of the plant. Care was taken to remove all ammonia from the air in which the plants were grown, and from the water and carbonic acid supplied to them; finally, after growth had ceased, the amount of nitrogen in the plant and in the soil was determined. In some cases a known quantity of nitrogenous compounds was supplied as manure; but all the results went to show that there was no gain of combined nitrogen during growth; the seed and manure at starting contained as much nitrogen as was found in the plant and soil at the end.

Similar experiments were carried out with the utmost precautions by the Rothamsted investigators, who likewise found no gain of nitrogen by the plant from the atmosphere. The following results, obtained by Lawes and Gilbert in 1858, will serve to show the agreement between the nitrogen supplied and recovered :

	Nitrogen in Seed (Grams).	Nitrogen in Soil and Plants.	Gain or Loss.	Nitrogen in Seed and Manure.	Nitrogen in Soil and Plants.	Gain or Loss
Wheat .	0·0078	0·0081	+0·0003	0·0548	0·0536	−0·0012
Barley . .	0·0057	0·0058	+0·0001	0·0496	0·0464	−0·0032
Oats . .	0·0063	0·0056	−0·0007	0·0312	0·0216	−0·0096
Beans . .	0·0750	0·0757	+0·0007	0·0711	0·0655	−0·0056
Peas . .	0·0188	0·0167	−0·0021	0·0227	0·0211	−0·0016
Clover .	...	...	...	0·0712	0·0665	−0·0047
Buckwheat .	0·0200	0·0182	−0·0018	0·0308	0·0292	−0·0016

It has sometimes been objected that the plants in these experiments made such a poor growth as compared with their normal development in the open air that they never attained their usual power of fixing nitrogen. However, Hellriegel's experiments on plants which were supplied with limited amounts of nitrogen showed that growth is practically proportional to the supply of nitrogen as long as that is below the maximum required by the plant. Field experiments at Rothamsted with leafy crops like mangolds, to which a very small amount of nitrogen was supplied in order to give them a start, showed that the increase thus produced was proportional to the nitrogen supplied, so that there is no evidence that even a plant which has begun to grow vigorously can then continue its development by taking nitrogen from the atmosphere.

From all these experiments the conclusion was drawn that cultivated plants are unable to " fix " atmospheric nitrogen, but obtain this indispensable element in a combined state from the soil together with the ash constituents ; and such was the opinion that prevailed for something like thirty years.

Notwithstanding the conclusive nature of all the laboratory experiments, there was still a residuum of facts obtained under field conditions which were inexplicable on the theory of the non-fixation of nitrogen, and these facts were chiefly connected with the growth of leguminous crops.

Boussingault's crop statistics have already been referred to; the following table gives a short summary of the kind of results he obtained:

Rotation.	Nitrogen. Kilos per hectare.	
	Supplied in Manure.	Removed in Crop.
Wheat, Wheat, Fallow	87·2	82·8
Potatoes, Wheat, Clover, Wheat or Turnips, Oats	202·2	268·5
Potatoes, Wheat, Clover, Wheat	182	339
Lucerne, 5 years	...	1035

The amount of nitrogen removed was equal to that supplied only when wheat was grown, but became progressively greater the more frequently leguminous crops occupied the ground.

At Rothamsted the following average quantities of nitrogen were removed per acre per annum in the crop, when mineral manures only were applied:

Wheat (24 years)	22·1
Barley (24 years)	22·4
Roots (30 years)	16·4
Beans (24 years, only 21 years in Beans)	45·5
Red Clover (22 years, only 6 years Clover)	39·8

In this case also the amount of nitrogen in the produce was much increased when a leguminous crop was grown.

Another of the Rothamsted experiments showed still more strikingly the accumulation of nitrogen by a leguminous crop. A piece of land which had been cropped for five years by cereals, without any nitrogenous manure, was divided into two portions in 1872, one being sown with barley alone, and the other with clover in the barley. In 1873 barley was again grown on the one portion, but the clover on the other, three cuttings of clover being obtained. Finally, in 1874, barley was grown on both portions. The quantities of nitrogen removed in the crops of 1873 and 1874 are shown in the table.

Nitrogen in Crop—Lbs. per Acre

1873	Barley	37·3	1874	Barley	39·1
1873	Clover	151·3	1874	Barley	69·4

Thus, the barley which followed clover obtained 30·3 lbs. more nitrogen than the barley following barley, though the previous clover crop had removed 114 lbs. more nitrogen than the first barley crop. An analysis of the soil was made in 1873, after the clover and barley had been removed; this showed down to the depth of 9 inches an excess of nitrogen in the clover land, despite the larger amount which had been removed in the crop.

In Soil after Barley	0·1416 per cent. Nitrogen
In Soil after Clover	0·1566 ,, ,,

In another experiment, land which had previously grown beans and then been fallow for five years, was sown with barley and clover in 1883, the clover being allowed to stand in 1884 and 1885. At starting the soil was analysed; the surface 9 inches contained on an average 2,657 lbs. per acre of nitrogen, whilst of nitrogen as nitric acid the soil only contained 24·7 lbs. per acre down to a depth of 6 feet. As a result of the three years' cropping with barley and clover, and then with clover only, an average amount of 319·5 lbs. of nitrogen was removed, yet the soil contained, on analysis at the end of the experiment, 2,832 lbs. of nitrogen per acre in the top 9 inches, or a gain of 175 lbs. per acre in the three years, making a total, with the crop removed, of nearly 500 lbs. of nitrogen per acre to be accounted for.

The consideration of field trials of this description led many observers to think that there still might be some fixation of free nitrogen, particularly by leguminous plants. Voelcker, in England, when discussing the power of a clover crop to accumulate nitrogen, expressed the opinion that the atmosphere furnishes nitrogenous food to that plant; in France, it was maintained by Ville; Berthelot also brought evidence to show that the soil itself, by the aid of its microscopic vegetation, assimilated some free nitrogen. Even in the laboratory experiments, some of Boussingault's results, and others of Atwater, in America, showed a gain of nitrogen. But the clearing up of the whole subject came with the publication, in 1886, of the researches of Hellriegel and Wilfarth. These investigators found that when plants were grown in sand and fed with nutrient solutions, the Gramineæ, the Cruciferæ, the Chenopodiaceæ, the Polygonaceæ, grew almost proportionately to the amount of combined nitrogen supplied; and, if this were absent, nitrogen starvation set in as soon as the nitrogen of the seed was exhausted. With the Leguminosæ, however, a plant was observed sometimes to recover from the stage of nitrogen starvation, and begin a luxuriant growth which lasted until maturity, though no combined nitrogen was supplied. In such cases the root of the plant was always found to be set with the little nodules characteristic of the roots of leguminous plants when growing under natural conditions. Further experiments were made in which the plants were grown in sterile sand, but as soon as the stage of nitrogen hunger was reached, a small portion of a watery extract of ordinary cultivated soil was added; whereupon, the plants receiving the extract recovered from their nitrogen starvation and grew to maturity, assimilating considerable quantities of nitrogen. The renewed growth and the assimilation of nitrogen were always found to be attendant upon the production of nodules on the roots. The nodules were found to be full of bacteria, to which the name of *Pseudomonas radicicola* has been given. They could only be produced by previous infection either by an extract of the crushed nodules or of a cultivated soil; in some cases (lupins, serradella) only by soil which had previously carried the same crop.

These results, though not at first accepted by Lawes and Gilbert, led to a repetition of the experiments, which brought out the fact that in their earlier trials with leguminous plants the necessary inoculation had always been wanting because of the great care that had been taken to prevent the entry of any accidental impurity. Eventually, both at Rothamsted and by other investigators, the conclusions of Hellriegel and Wilfarth were confirmed, that when leguminous plants are grown under sterile conditions, without a supply of combined nitrogen there is very limited growth, no formation of nodules, and no gain of nitrogen. But when the culture is seeded with soil extract there is luxuriant growth, abundant nodule formation, and coincidently, great gain of nitrogen, many times as much in the products of growth as in the seed sown. Gilbert also showed that there is a gradual accumulation and then withdrawing of nitrogen from the nodules. Lastly, Schloesing *fils* and Laurent, by growing Leguminosæ in closed vessels, and analysing the air before and after growth, found an actual disappearance of nitrogen gas, agreeing with the amount gained by the plant during growth. Thus, a conclusion was reached that the leguminous plants can assimilate and fix the free nitrogen of the atmosphere by the aid of bacteria living symbiotically in the root nodules—a conclusion which served to explain, not only the discrepancies in the previous experiments, but the long-accumulated experience of farmers that crops like clover and lucerne enrich the soil, and form the best preparation for cereals like wheat, which are particularly dependent on an external supply of nitrogen. The mechanism of the fixation of free nitrogen is still incompletely understood. It has been found possible to grow these bacteria apart from the leguminous plants, if they are cultivated on a medium containing the ash constituents of the plant and some carbohydrate like dextrose or maltose. A trace of some nitrogenous compound is also necessary and is best supplied as an extract of a leguminous plant. The quantities of nitrogen fixed in this way are always, however, very much smaller than are fixed by a leguminous plant on whose root the nodules are well developed. To fix the nitrogen, some expenditure of energy is required, and this is derived from the combustion of carbohydrate supplied to the bacteria by the higher plant ; indeed it has been observed that the nitrogen fixation and general growth of the Leguminosæ is stimulated by a supply of sugar or other carbohydrate to the soil. The organism, *Pseudomonas* or *Bacillus radicicola*, appears to be capable of considerable modifications ; in the nodules it forms rather large rod- or Y-shaped organisms, but if an active subculture be obtained by inoculation from a nodule into a non-nitrogenous medium as described above, excessively minute rod-shaped organisms appear.

These rods soon undergo some change whereby their contents become segregated into points of the rod, consequently on staining it appears banded. At this stage the rods may become branched and take on the Y-forms characteristic of the organism in the nodule, but this occurs only in response to the introduction of particular materials into the medium. The segregation continues until the portions are liberated from the mother cell as cocci, not motile at first, but which soon develop flagella and become active. The cocci then pass into the non-banded rod stage, and lose their flagella.

It is in the " swarmer " coccus stage that the organism infects the host plant by passing into the root-hairs, a process which seems to depend on some secretion from the plant whereby the developing bacteria form minute slimy patches on the root-hair. It has been shown by Thornton that the degree of motility and the range of action of the motile form are influenced by the nature of the soil solution and that the rate at which the infection will spread in the soil is greatly increased by the presence of a trace of soluble phosphate.

Much investigation has also been applied to the question of whether there is only one kind of bacterium living in symbiosis with all the Leguminosæ, or whether there is not a definite race appropriate to each species of leguminous plant, with which it alone can bring about nitrogen fixation to the full extent. The earliest investigations had already shown that lupins and serradella did not develop nodules when infected with an ordinary garden soil, but only when an extract was added from a sandy soil on which these plants had been previously grown ; and Nobbe brought further evidence to show that, though there is very widely distributed in the soil an organism which will cause some nodule formation and fixation of nitrogen, yet it becomes so modified by growing in symbiosis with the different leguminous plants, that the best results are only obtained when each species is directly infected from nodules taken from the same kind of plant.

Accordingly, he proceeded to the introduction, on a commercial scale, of pure cultivations on a gelatine medium of the races of bacteria appropriate to each of the leguminous plants grown as field crops. The jelly, which was called " Nitragin," was to be dissolved in a large bulk of water and sprinkled over the seed before sowing ; thus ensuring inoculation with the appropriate organism, which might not happen to be present in the soil. Nitragin failed to fulfil the expectations which were formed at its introduction, partly because of the nitrogenous character of the medium, in consequence of which the organisms possessed very little vitality or power of fixing nitrogen. Since that time, however, several other methods of cultivating the organism for inoculation purposes have been introduced, either by growing it on an agar jelly, which contains practically no nitrogen (Hiltner), by drying up cotton-wool which has been soaked in an active liquid culture (Moore), or by drying soil which has been treated in the same way. Active liquid cultures can now be obtained from most laboratories. The culture thus obtained is added to a large bulk of water, containing separated milk to protect the organisms from substances excreted during germination, and the seed is dipped into it and allowed to dry before sowing. Calcium di-acid phosphate at the rate of 1 per 1,000 should be added to the dilute milk in order to promote the activity of the motile forms of the organism. The culture may also be sprayed over the ground or absorbed by a large quantity of earth which is afterwards sown. The results of such inoculation are very conflicting ; where the land has been regularly under cultivation and has carried the leguminous crop in question many times previously, nodules are practically always formed whether the seed be inoculated or not. In such cases inoculation can be beneficial only if the bacteria introduced either belong to a more vigorous race of nitrogenous fixers than those normally present in the soil or are more specifically adapted to that particular crop. It has not as yet been conclusively demonstrated that such improved races can be cultivated in the laboratory, or that they can maintain themselves in the soil in competition with the kindred organisms already present. It should, moreover, be borne in mind that even if such improved races of the nodule-forming organism can be introduced to the plant, the improvement they can produce in the yield is likely to be something of the order of a 10 per cent. increase, a gain which is only really perceptible after careful and continued field experiments, and one not to be detected by the ordinary farmer's eye. Of a very different order are the results attained by inoculation when the land contains none of the appropriate organisms ; inoculation will then change a stunted, sickly-looking growth into a profitable crop. It is only in special cases that land devoid of the nodule organisms is to be met with, most commonly when land is being brought under cultivation for the first time, as in breaking up a virgin soil or in reclaiming heath and bog land. Such peaty and heathy soils, which are devoid of carbonate of lime, rarely carry any leguminous plants the nodules of which could supply the necessary bacteria to farm crops like clover and lucerne ; when such land has been reclaimed and limed an inoculation is advisable before sowing a leguminous crop.

Similarly when the cultivation of such leguminous crops as lucerne or even sainfoin is being extended into districts where they have not been grown previously, an inoculation is often necessary before the roots will nodulate freely and the plant make its proper growth. Lucerne grown for the first time on heavy land in a new district has been observed to fail completely, the failure being attended by a complete absence of nodules from the roots. Success does not, however, invariably follow inoculation. In the first place, it may be necessary to bring the soil itself into the proper condition for the growth of both crop and the bacteria, the natural absence of which is of itself evidence that the soil is unsuited to their maintenance. Liming and dressings of basic slag and potash salts are generally the necessary preliminaries to any satisfactory growth of leguminous crops on indifferent soils. Even then the first inoculation may show comparatively little effect, the plant still remaining weakly, though most of the individuals may show nodules. The inoculation only supplies a very limited number of bacteria compared with the population in a normal soil. It is only when the crop comes to be sown a second time that vigorous growth is obtained. It is within the experience of the author (A. D. H.) that a first sowing of lucerne on land that had never carried the crop before gave weakly, unnodulated plants. A culture of nodule organisms was sprayed over in the early spring without benefit, whereupon the crop was ploughed up and resown, the seed being inoculated before sowing. The plant was still poor, though generally nodulated ; accordingly it was again ploughed up and resown, with the result that a good crop of lucerne was established.

A series of trials made from Rothamsted seem to show that the limitation of the growth of lucerne in Great Britain to a small number of counties in the south and east of England is not so much a matter of climate as of the presence or absence in the soil of the inoculating organisms.

They may be presumed to have arrived originally by accident upon the imported seed and gradually to have established themselves in the lighter neutral soils of those counties which were first in touch with continental agriculture. Their spread into the rest of Great Britain has been slow because the first attempts to cultivate the crop without inoculation inevitably failed and did not encourage repetition. Now it has been demonstrated that with suitable inoculation and manuring, crops of lucerne can be established even in the north of England and in Scotland.

Inoculation with soil from a field that has previously grown the crop about to be sown has often proved a signal success in reclaiming the poor heath lands of East Prussia, by the system of green manuring worked out by Dr. Schultz at Lupitz. Very large areas of barren sandy heath land have been reclaimed and rendered fit for the cultivation of the ordinary crop by a system of growing lupins and ploughing in the green crop. Mineral manures alone are employed, latterly basic slag and the Stassfurt potash salts ; the lupins accumulate nitrogen from the atmosphere, thus gradually there is built up both humus to bind together the loose sand and make it retentive of moisture, and also a store of nitrogen for the nutrition of succeeding crops. The soil of a field growing lupins every year from 1865 was found in 1880 to contain 0·087 per cent. of nitrogen in the surface 8 inches, as compared with 0·027 per cent. in an adjoining pasture. By 1891 the proportion of nitrogen had increased to 0·177 per cent., despite the annual removal of the lupin crop and the fact that the manuring had been with phosphates and potash only. It is in reclaiming these heath lands that have not previously been under cultivation, nor, in many cases, carried any leguminous vegetation whatever, that soil inoculation from land previously cultivated has given successful results. Dr. Salfeld of Hanover has recorded several cases of the successful cultivation on a large scale of various leguminous plants, beans, clover, serradella, lupins, only after previous inoculation with soil. The experiments were made on both peaty (moor) and sandy soils, on which, without inoculation, leguminous plants made but little growth and developed no nodules. Success followed when about 8 cwt. per acre of soil from a field that had previously carried the crop in question were sown broadcast over the land in April, and harrowed in just before seeding. In one case, over 7 tons per acre of green serradella were grown where the land had been treated with 8 cwt. of soil from an old serradella field, whereas the crop failed after germination where no inoculation had been practised.

Fixation of Nitrogen by Free-living Bacteria

As already indicated, Berthelot attributed to the soil itself the power of fixing a small quantity of atmospheric nitrogen, a power which was lost when the soil was sterilized and maintained under conditions preventing infection. This gain of nitrogen was independent of the small amount of ammonia absorbed by soil from ordinary air, which always contains a trace of ammonia ; and at first it was attributed to the microscopic green algæ that clothe the surface of ordinary moist soil. The experiments of Kossowitsch, and of Krüger and Schneidewind, have, however, shown that the growth of pure cultures of these algæ is dependent on a supply of combined nitrogen, and that no fixation of free nitrogen takes place whether the algal growth be small or large. It is possible, however, that they may live in symbiosis with nitrogen-fixing bacteria and supply the carbohydrate, by the combustion of which the energy needed for the fixation of nitrogen by the bacteria is obtained. More recently, however, several organisms have been isolated from the soil, which are capable, when growing in a free state, of fixing nitrogen drawn from the atmosphere, and it is to these that the gains of nitrogen observed by Berthelot must be attributed. Vinogradsky was the first to isolate an organism of this type, which, when grown under anaerobic conditions and supplied with soluble carbohydrate, breaks the latter down with the formation of butyric and other acids, and at the same time draws some of the gaseous nitrogen present into combination. This particular organism *Clostridium Pastorianum* is very widely diffused and can readily be isolated from pond mud and similar material, where organic matter is decaying under comparatively anaerobic conditions. The extent of the nitrogen fixation is, however, small ; in the laboratory not more than 2 to 3 mgrms. of nitrogen are brought into combination for each gram of carbohydrate oxidized. By far the most effective of the nitrogen-fixing bacteria that are free in the soil is a large organism, named by its discoverer, Beijerinck, *Azotobacter chroococcum.* It may be easily isolated from most soils by adding a small portion of soil to 50 c.c. of a culture medium containing per litre 10 grams of mannite or glucose, 0·2 gram each of potassium phosphate, magnesium sulphate, and sodium chloride, and 0·1 gram of calcium sulphate, half a gram of calcium carbonate being also added to each flask. The solution and its flask and plug of cotton-wool are previously sterilized by heat. After inoculation, the flask is placed in an incubator, and after a week's time a considerable fermentation will be observed to have taken place, attended by the evolution of gas and the formation of a brown scum upon the surface. By making a subculture in a similar medium, inoculated with a trace of the brown scum, a fairly pure growth of the *Azotobacter* can be obtained for examination, or the amount of nitrogen fixed may be determined by Kjeldahling the contents of the flask.

Azotobacter chroococcum is a large oval organism, 4 to 5 μ in length and 3 μ in width, which differs from most bacteria, in containing glycogen, so that it stains a deep brown colour with a solution of iodine, a method which is convenient for the observation of the organism. It is aerobic, and is, in fact, a strong oxidizing agent, the dextrose or other carbohydrate which it requires being converted by it into carbon dioxide and water, together with small quantities of lactic and acetic acids, alcohol, and sometimes butyric acid.

A very characteristic by-product is the dark brown or black pigment from which the organism derives its specific name, a pigment which may play its part in the usual coloration of humus.

As a rule, about 9 or 10 mgrms. of nitrogen are fixed for each gram of carbohydrate oxidized, but the ratio obtained varies considerably under different conditions; cultures which have been repeatedly transferred, being, as a rule, less effective than the impure culture derived directly from the soil.

Azotobacter chroococcum and its kindred forms are widely distributed in soils from all parts of the world; it has been found in most cultivated soils, and the author has observed it in virgin soils from East Africa, India, New Zealand, Egypt, Russia, Monte Video, Ohio, and Sarawak.

It is, however, not to be discovered in acid soils; the presence of calcium carbonate appears to be essential to its development. Certain minor differences are to be seen in the *Azotobacter* organisms present in the soil from different parts of the world. From tropical and semi-tropical soils in East

Africa, for example, a form has been isolated which is a very effective fixer of nitrogen, but which differs from the normal in not giving rise to the brown pigment ; another form, again, from Monte Video gives rise to a green fluorescence in the culture medium.

The amount of nitrogen fixed by *Azotobacter* may easily be rendered evident by an increased yield of crop. Koch treated soil in pots with large quantities of sugar, 2 per cent., 4 per cent., and even more of dextrose, and then sowed oats, buckwheat, etc. At first the sugar was injurious, and the first crop suffered in consequence ; but the proportion of nitrogen in the soil increased, and the second and third crops were far greater than those in the check plots of untreated soil. When the soil, after the application of the sugar, was placed in an incubator for a month, in order to complete the oxidation of the sugar, the increased yield due to nitrogen fixation was also seen in the first crop.

At Rothamsted, portions of the barley plots, one that had been for a long time unmanured and another that had been receiving phosphates and potash but no nitrogen, were treated with sugar or starch at the rate of 1 ton per acre. In the earlier trials, when these carbohydrates were applied in the spring before sowing, the crop was depressed by the carbohydrate ; but when the time of application was changed to the autumn, a marked increase of yield followed the application of carbohydrate on the plot well supplied with all the elements of fertility except nitrogen, though the effect was small upon the unmanured plot. The results are given in the table on page 189.

In the earlier trials, with a spring application of the carbohydrate, the normal temperature of the soil was too low to permit of the development of *Azotobacter* and the fixation of nitrogen. Other organisms attacked the carbohydrate and by their multiplication reduced the small supply of nitrogen available to the crop. Possibly, too, some of the products of their action on the carbohydrate were injurious. But with an autumn application in the still warm soil, nitrogen fixation goes on actively, and some of the material thus absorbed

Rothamsted. Effect of Carbohydrate on Succeeding Barley Crop

Date of Application, 1 ton per acre.	Unmanured since 1852. Total Produce, lb. per acre.		Phosphoric Acid and Potash, but no Nitrogen since 1852. Total produce, lb. per acre.	
	Without Sugar.	With Sugar.	Without Sugar.	With Sugar.
6th March 1906	1497	...	2485	...
17th Jan. 1907*	1604	1192	3578	3249
4th Feb. 1908 .	1068	648	1820	1404
19th Feb. 1909 .	1529	1352	3148	2261
27th Sept. 1909.	1633	1557	2082	2502
22nd Sept. 1910	968	1025	1244	1915

* Starch instead of sugar.

from the air becomes available for the crop in the following spring.

To the *Azotobacter* and kindred organisms must certainly be ascribed a large part in preparing and maintaining the world's stock of combined nitrogen. It is customary to regard such virgin soils as the black soils of the Russian Steppes, of Manitoba, and of the Argentina, as rich in nitrogen because of the accumulation of the vegetable débris of many thousands of years. Under the climatic conditions of the "steppe," vegetation is active in the spring, then the progressive desiccation suspends growth but at the same time "fixes," as it were, the vegetable matter already accumulated, because normal decay is arrested by the lack of water. Under such conditions, however, since plants other than the Leguminosæ do not fix nitrogen themselves, there could in this way be no addition to the original stock, which would only circulate from the soil to the plant and back to the soil again. The spring growth, however, causes a continual addition to the soil of the carbon compounds that the plant derives from the atmosphere, and this is material which the *Azotobacter* can oxidize, and so derive the energy required for the fixation of nitrogen. It is the constant return to the soil of oxidizable organic matter that differentiates the wild from the cultivated land, and renders possible the long-continued storing up of nitrogen in the virgin soils.

Interesting evidence on this point may be derived from the Rothamsted experiments; on the Broadbalk wheatfield the unmanured plot has, during the fifty years 1844-93, yielded a crop containing on the average 17 lbs. of nitrogen per acre per annum. Analyses of the soil at the beginning and end of the period showed a decline in the amount of nitrogen equivalent to a removal of 12 lbs. per acre per annum, and the rainfall is known to bring down between 4 and 5 lbs. per acre per annum. The annual withdrawal in the crop would thus be closely balanced by the loss experienced by the soil and the additions, were there not other unknown withdrawals in the weeds which are removed from the plot, and in the nitrates that are washed down into the subsoil and the drains. Doubtless, neither of these two withdrawals are large, but because of their existence, unbalanced by any corresponding falling off in the nitrogen content of the soil, it must be concluded that even on the arable land some small restorative action is going on. A portion, however, of the same field has been covered with a wild vegetation of weeds and grasses for the last twenty-five years, and this is never cut or harvested, so that all the débris falls back on the land just as it would on a virgin soil. Analysis of samples of this soil taken in 1881, when it ceased to be under cultivation, and in 1904, showed an annual accumulation of nitrogen of more than 100 lbs. per acre. The enormous difference in the fixation on this plot as compared with the unmanured plot carrying wheat, must be set down to the difference in the supply of non-nitrogenous carbon compounds to the two plots; in the one case the wheat is all removed except a small portion of root and stubble; in the other the whole of the vegetable growth falls back on the land. The wild vegetation on this plot did include a considerable proportion of leguminous plants, but a similar, though smaller, accumulation of nitrogen was observed in another plot of land which had been allowed to run wild in the same manner, but which carried no leguminous vegetation in consequence of the small amount of calcium carbonate in the soil. These two plots present a very close parallel to the actions that must have been taking place in all virgin soils where the soil similarly contains the *Azotobacter* organism. Doubtless also some of the value of laying down land to temporary pasture must be due to the accumulation of nitrogen by the same agency, because we know that land under grass accumulates carbon compounds from the roots and stubble that are not removed during grazing.

Nitrification

It has long been known that when any organic compound of nitrogen is applied to the soil it becomes eventually oxidized to a nitrate, which is, as a rule, the compound of nitrogen taken up by cultivated plants, the Leguminosæ excepted. The potassium nitrate collected from Indian soils, the calcium nitrate made artificially in nitre beds in Europe, owe their origin to this oxidation of organic compounds of nitrogen. That the process was a biological one was first indicated by Müller in 1873, but any widespread recognition of the fact did not take place before the work of Schloesing and Muntz in 1877. These investigators showed that the formation of nitrates in the soil ceased at temperatures below 5° and above 55° C., that it could be stopped by chloroform vapour and similar antiseptics, and that the soil lost entirely its power of nitrification if it were heated to the temperature of boiling water. The investigations of Warington confirmed these results, and brought to light the further fact that there were two stages in the oxidation process, one being the formation of a nitrite, followed by the conversion of this nitrite into the completely oxidized product. It was found possible to obtain cultures that would only push the oxidation to the nitrite stage, thus indicating that there must be at least two organisms concerned in the complete nitrification process. The further study of the organisms was for a long-time hindered by the fact that they could not be got to grow upon the gelatinous media employed in the ordinary methods of isolating specific bacteria; and though P. F. Frankland, by a dilution method, succeeded in isolating and describing a nitrifying bacterium, it was not until 1890 that Vinogradsky cleared up the problem. He prepared a solid nutritive medium containing no organic matter but with silica in its gelatinous form as a basis, and thus was able to separate nitrifying bacteria from the large number of other species simultaneously present in the soil. Vinogradsky was able to isolate two species of bacteria capable of transforming ammonium compounds into nitrites. One of these, termed *Nitrosomonas europœa*, was obtained from all the soils of the old world he examined; the other, ascribed to the genus *Nitrococcus*, was peculiar to the soils of America and Australia. The former occurs both as a single, free-swimming form, and clustered together in a colony or zooglœa state.

Finally, there appears to be one type of organism only, included in the genus *Nitrobacter*, which oxidizes the nitrites to nitrates. Vinogradsky and other observers have worked out the conditions of life of these nitrifying organisms—the limits of temperature for their growth, 5° and 55° C., have already been given; the optimum temperature is about 37° C. Their action is much restrained by the presence of organic matter, or any quantity of alkaline carbonates or chlorides; at the same time, some base[1] must be present to combine with the nitrous or nitric acids produced, for nitrification ceases as soon as the medium becomes at all acid. Whilst calcium carbonate is the substance which, as a rule, is effective to this end, many organic salts will also supply the necessary base. Ammonium salts of the strong acids will not nitrify directly in the absence of a base, and the function of the calcium or magnesium carbonate usually added is to form, by double decomposition, ammonium carbonate, which the nitrifying organisms can attack. The salts formed by the interaction of the colloidal complex with ammonium salts can be nitrified directly, but not, however, the ammonium humate formed by the corresponding interaction of ammonium salts and humus. Humus itself does not inhibit nitrification, and, indeed, the organisms can be brought to tolerate considerable quantities of other organic matter, by transferring them into successively stronger solutions. The organisms are able to obtain the carbon necessary to their growth from carbonates in the culture medium or carbonic acid in the air ; the energy necessary to decompose the carbon dioxide and fix the carbon is derived from the oxidation of the ammonia, about 35 parts of nitrogen being oxidized for each part of carbon that is fixed. The nitrifying organisms are chiefly confined to the cultivated surface layer of the soil. Warington found that, in the close-textured Rothamsted soil they were by no means uniformly distributed below the top 9 inches, and that they were never present, except accidentally, in the subsoil below a depth of 2 feet. It has also been shown that they are entirely absent from many heath and moor soils, even in the surface layer. They are abundantly found in the water of shallow wells and rivers.

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[1] Instruction sur la fabrication du nitre :—Par *les régisseurs généraux des poudres et salt pêtres*, 1777, " Elles doivent l'être toujours avec une addition de terre calcaire qui puisse servir de base à l'acide nitreux."

Further investigations show that though nitrate production is the normal end-process in the breakdown of nitrogenous substances into plant food, from which it follows that the rate of production of nitrates is some measure of the fertility of the soil, yet the nitrate-producing bacteria are, as a rule, able to convert the ammonia immediately it is presented to them, and the real limiting factor in nitrate production is the activity of the ammonia-producing organisms. The amount of free ammonia in neutral soils is always very small, one or two per million, whereas the nitrate may amount to 50 to 100 parts per million. This is because the ammonia is transformed as fast as it is produced, and nitrifying organisms are always able to keep pace with the output of ammonia if by any means that can be stimulated. In acid soils, where nitrification is slowed down or at a standstill, the higher plants doubtless take in the nitrogen they require as ammonia ; indeed certain modifications in the colour of the crop and its habit of growth appear to follow when it is deriving its nitrogen from ammonia and not from nitrates. In considering the fertility of the soil the ammonia-making and nitrifying organisms must be regarded as one group, which do the final preparation of the organic nitrogen residues for the food of the higher plants and upon the activity of which, particularly of the former, the rate of production of available plant food depends.

Summing up the above facts, it is seen that for the active production of nitrates from the organic compounds of nitrogen present in the soil—and this is necessary if the crop is to be kept supplied with the nitrogen required for its growth—the following conditions are requisite : The presence of the ammonia-making and nitrifying organisms in sufficient quantities, a certain degree of temperature, sufficient moisture for the development of the bacteria, free aeration of the soil to supply the oxygen necessary, and a base to neutralize the acids as they are produced.

The scanty number of ammonia-making and nitrifying bacteria in any subsoil below the cultivated layer helps to explain both its sterile nature when brought to the surface, and the difficulty and length of time required to develop a state of fertility, especially when dealing with a clay soil in which percolation and aeration have been deficient.

The effect of a low temperature in checking the formation of nitrates is well seen in the way the growing corn turns yellow through nitrogen starvation whenever a cold and drying north-east wind chills the ground in spring : the bright green colour returns as soon as warmer and moister soil conditions restore the activity of the bacteria in the surface layer. King found in the top foot of soil when oats were turning yellow only 0·26 parts of nitric nitrogen per million of dry soil, whereas in soil where the oats were green on the same date there were 2·55 parts of nitric nitrogen per million, itself a small amount. The greater warmth of a light soil also causes it to form nitrates quickly in the spring and so assists in producing an early growth.

But in obtaining early crops, even when the land is rich, a dressing of ready-formed nitrate is often of the greatest assistance, for the development of very early crops may easily outstrip the rate at which the nitrates they require can be formed in the still unwarmed soil. Nitrates are much more freely formed in the summer than in the winter, and as they are not retained by the soil, they may easily be washed away when the crop has been removed, unless weeds or a catch crop sown to that end are present to take up the nitrates and store them as organic compounds of nitrogen for the future enrichment of the land.

The need for aeration in connexion with the nitrifying process has already been alluded to when discussing drainage : all processes of working and cultivating the soil assist nitrification, both by the thorough aeration they effect, and by the mere mechanical distribution of the bacteria into new quarters, where there are fresh food supplies. In some experiments of Dehérain's he found that the drainage water from pots of cultivated soil, which had been sent from a distance, and thus much knocked about in travelling and filling into the pot, contained as much as 466 to 664 parts of nitrogen as nitric acid per million. The drainage water from the Rothamsted wheat plots contains only from 10 to 20 parts per million ; even the cement tanks at Grignon, 2 metres cube, into which the soil had been filled, gave drainage water containing only 39 parts of nitric nitrogen per million. In another experiment a quantity of soil was thrown upon a floor, and worked about daily for six weeks ; on analysis it contained 0·051 per cent. of nitric nitrogen, as against 0·002 per cent. of nitric nitrogen in the same soil left *in situ*. The diagram (Fig. 18), due to King, shows the dependence of nitrate production on temperature and the cultivation of the soil. The lower curve shows the amount of nitrate in parts per million in dry soil in the top foot of land, which was not being cultivated because it carried clover and oats. The upper curve shows the same results obtained on well-tilled land carrying maize and potatoes. On the cultivated land the proportion of nitrates rises rapidly until the end of June, when the crop begins to draw freely upon them, and reduces them to a minimum throughout August and September.

One of the best examples of the manner in which the thorough working and aeration of a warm soil promotes

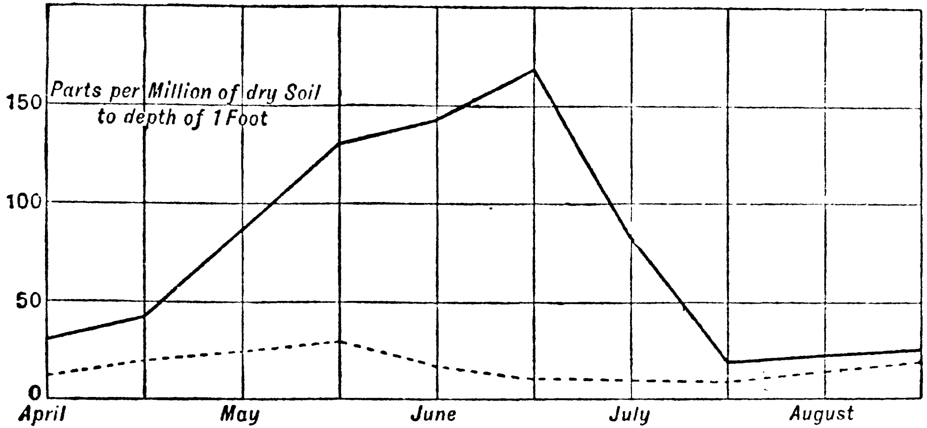


FIG. 18.—Nitrates per million parts Dry Soil, 1 foot deep, Cultivated and Uncultivated.

nitrification is seen in the management of the turnip crop as usually grown in this country. Though shallow-rooted, and taking away large quantities of nitrogen per acre, it is usually grown with but little nitrogenous manure ; phosphates with a little dung or with a comparatively small nitrogenous dressing, being sufficient. The rest of the nitrogen is derived from the rapid production of nitrates, due to the very thorough working of the soil in the warm season of the year that is characteristic of the cultivation of the turnip crop. The production of nitrates by cultivation for the benefit of a succeeding crop in bare fallowing, or of an adjoining crop as in the Lois-Weedon system of alternate husbandry, has been already alluded to. At Rothamsted, nearly 60 lbs. per acre of nitric nitrogen were found in October in the top 27 inches of soil that had been fallowed, as against about half that amount in land that had been under crop. The unmanured alternate wheat and fallow plots showed in September 1878, to a depth of 18 inches, 33·7 lbs. of nitric nitrogen per acre after fallow, and only 2·6 lbs. after wheat. In land occupied by cereal crops the drainage waters show that there is practically no nitrate left in the soil by May, or, at the latest, June ; they reappear again towards the end of July or in August, and after harvest, if rain falls, and especially if the land be ploughed, nitrification becomes very active. It depends upon the rainfall of the autumn and winter whether these nitrates, formed after harvest, are retained for the succeeding crop or are washed out of the soil. To sum up, increased nitrification, together with the conservation of soil moisture and the warming of the surface soil, are among the chief benefits derived from all forms of surface cultivation.

Attempts have been made to estimate the fertility of soil by determining the rate at which it will induce nitrification in suitable media, this being taken as a measure of the number of nitrifying organisms present. But, as has been seen, the activity of the ammonia-making organisms is the limiting factor in the production of nitrates ; in consequence it is their numbers that should be determined. A better indication is obtained by determining the rate of formation of nitrate within a mass of the soil ; the difficulty attending the operation is, however, that of securing standard conditions of moisture and mechanical condition of the soil.

Denitrification

The term denitrification is most properly applied to the reduction of nitrates to nitrites, ammonia, or particularly to gaseous nitrogen, which is brought about by bacterial action under certain conditions. Of late, however, the term has been more loosely used to denote any bacterial change that results in the formation of gaseous nitrogen, whether derived from nitrates, ammonia, or organic compounds of nitrogen.

In a paper published in 1882, Warington described an experiment in which sodium nitrate was applied to a soil saturated with water ; after standing for a week, the nitrate was washed out of the soil, part of it had disappeared, and part had become nitrite. The total of both nitric and nitrous nitrogen only amounted to 20·9 per cent. of that which had been originally applied. That the nitrate had been reduced to gaseous nitrogen was seen by the development of transverse cracks filled with gas in the soil, and it was concluded that some of the nitrogen applied in manures and unaccounted for in crop and soil may well be due to the reduction of nitrates to gas, by the combustion of organic matter with the oxygen of the nitrate, especially in ill-drained soils in wet weather. Gayon and Dupetit, in 1886, isolated two organisms from sewage which would reduce nitrates to gas in the presence of organic matter, the action being chiefly carried on when oxygen was absent ; it came to a standstill when plenty of air was supplied, so that the organism had no need to attack the nitrate to obtain oxygen. Both in their experiments and in others, the presence of an abundant supply of soluble organic matter was one of the necessary conditions for the destruction of the nitrates. The denitrifying bacteria are widely distributed. Warington found, out of thirty-seven species of bacteria examined, only fifteen failed to reduce nitrate, twenty-two reduced it to nitrite, and one of them liberated gas. P. F. Frankland, again, found that fifteen out of thirty organisms derived from dust or water would reduce nitrate to nitrite. In fact, a large number of bacteria, when deprived of oxygen and in contact with abundant organic matter, will obtain the oxygen, which they normally require for the breaking up of the organic matter, at the expense of the nitrate.

Many experiments, in which farmyard and other organic manures have been employed in conjunction with nitrate of soda and similar active compounds of nitrogen, have shown a smaller crop for the manures used together than when either was employed singly. These results were particularly apparent when large quantities of material like fresh horse-dung or chopped straw were used in pot experiments. With well-rotted dung, the effect of organic material in depressing the yield which should be given by the nitrate was not so great.

The nature of the results obtained may be seen from the following table, which gives the percentage recovered in the crop of the nitrogen supplied in the manure, when used alone, or in conjunction with fresh horse-dung :

PERCENTAGE OF NITROGEN RECOVERED (WAGNER)

	Per cent. recovered when used alone.	When used with Horse-dung.
Nitrate of Soda . . .	77	52
Sulphate of Ammonia . .	69	50
Urine	69	40
Grass	43	20

Numbers of similar experiments in pots have been recorded. In some cases the use of fresh dung has even resulted in a smaller crop than was obtained without any manure at all ; but it should be noted that very large amounts of the organic manures were used, equivalent to 100 tons or more per acre. Similar results have, however, been recorded in field trials, as in some experiments of Krüger and Schneidewind's, where fresh cow-dung was applied at the rate of 23 tons per acre, horse-dung, 21 tons per acre, and wheat straw at 5·8 tons per acre, on 10th July. These three plots were in part cross-dressed with urine or with nitrate of soda, each supplying 43 lbs. of nitrogen per acre. Two successive crops of mustard were immediately grown, and the amount of nitrogen removed by the crop was ascertained. Compared with the wholly unmanured plot, the cow-dung alone slightly depressed the crop, about 1½ lbs. per acre less nitrogen being recovered; the horse-dung produced a depression of nearly double this amount; the wheat straw produced the greatest depression, its crop containing about 18 lbs. per acre less nitrogen than that given by the unmanured plot. Where straw was used with nitrate of soda the two gave a crop containing 23 lbs. less nitrogen per acre than the nitrate alone; where urine was used alone, the produce contained 25 lbs. more nitrogen per acre than when it was used in conjunction with cow-dung and straw.

In fine, all the results pointed to the same conclusion—that large amounts of fresh organic manure not only do not themselves help the crops, but diminish the effect of other rapidly acting nitrogenous manures like nitrate of soda, sulphate of ammonia, or urine.

The action cannot, in the two latter cases at least, be put down to denitrification proper, unless it is supposed that nitrification and subsequent denitrification can proceed practically simultaneously in the same soil. It must either be attributed to the fact that nitrification is very much checked by the presence of large amounts of organic matter; or to the conversion of readily available nitrogen into a comparatively insoluble albuminoid form in the actual material of the enormous numbers of bacteria that are developed by the free food supply; or, lastly, to those fermentation changes of organic nitrogen compounds which result in the liberation of free nitrogen. Several of these changes may take place together; the essential point is that nitrification does not go forward in the presence of much organic matter, which instead favours all the bacterial processes resulting in the development of free nitrogen.

The conditions, indeed, which prevailed in these experiments are scarcely comparable with the ordinary practices of agriculture. Enormous quantities of fresh organic manure were employed immediately before the crop was sown, the temperature of the pots, or of the ground in the field experiment quoted, was very high, so that it is easy to see that an abnormal condition, both as regards nitrification and the supply of oxygen and water, must have been developed.

There are not lacking both long-continued experiments and ordinary farming experience to show that nitrates and other artificial manures can be used in conjunction with dung with the best effects.

For example, the mangold crop at Rothamsted shows the following average results for the recovery of nitrogen from various nitrogenous manures used first with mineral manures alone and then with annual dressings of 14 tons per acre of farmyard manure, a quantity that never would be employed so frequently in practice :

Nitrogenous Dressing.	Yield. Tons per acre.	Nitrogen.		
		In Manure.	Recovered in Crop.	Percentage recovered per 100 in Cross-dressing.
PLOTS MANURED WITH PHOSPHATES AND ALKALINE SALTS				
Nitrate of Soda . .	17·95	86	67·2	78·1
Ammonium Salts .	15·12	86	49·3	57·3
Rape Cake . .	20·95	98	69·4	70·9
Ammonium Salts and Rape Cake . .	24·91	184	103·0	56·0
PLOTS MANURED WITH DUNG				
Nothing . . .	17·44	200	63·3	31·6*
Nitrate of Soda . .	24·74	286	115·8	61·0
Ammonium Salts .	21·73	286	105·6	49·2
Rape Cake . .	23·96	298	111·1	48·8
Ammonium Salts and Rape Cake . .	24·05	384	129·8	36·2

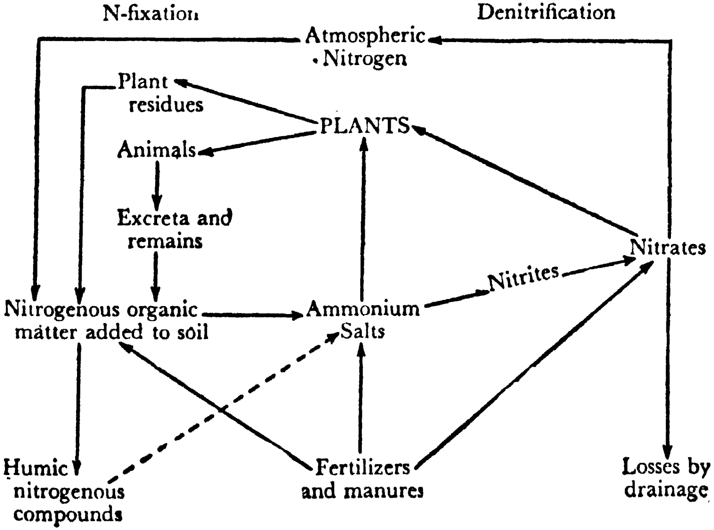
* Percentage of nitrogen in dung recovered.

It will be seen that all the nitrogenous cross-dressings produce an increase of crop when added to the farmyard manure. When the cross-dressings are used on plots receiving only non-nitrogenous manures, the nitrogen recovered varies between 56 and 78 per cent. of that supplied in the manure; when they are used in conjunction with dung, the recovery of nitrogen in the increased yield above that produced by dung alone varies between 36 and 61 per cent. That the recovery is smaller in the latter cases is due to the fact that with such excessive amounts the yield ceases to be proportional to the supply of nitrogen, being limited by other factors.

Denitrification is only likely to cause rapid loss of nitrogen when large quantities of nitrate are applied to undrained or sour land, or when they are used with excessive amounts of fresh dung, which has not been rotted and so deprived of much of its soluble organic matter. Of course, a steady loss of nitrogen due to such causes as have been discussed above must also be expected wherever large quantities of organic nitrogenous manures are accumulating in the land. If, for example, we compare plots 2 and 3 of the Broadbalk wheat field at Rothamsted, the latter of which is unmanured and the former receives dung containing 200 lbs. of nitrogen per acre every year, we find that at the end of the fifty years, 1844–93, the dunged plot contained in the top 18 inches about 2,680 lbs. more nitrogen than the unmanured plot, or a mean annual accumulation of 50 lbs. The extra crop grown on the dunged plot would remove a further 31 lbs., thus leaving 119 lbs. per annum to be accounted for, either as nitrogen washed away in the drainage water or lost as gaseous nitrogen by denitrification processes. After a wet winter the wheat crop, especially upon heavy land, often shows patches of lighter colour and poorer growth. These are generally attributed to the washing out of the autumn-formed nitrates, but it is more probable that the shortage of nitrogen is due to denitrification consequent upon water-logging. Indeed denitrification and the evolution of gaseous nitrogen, rather than leaching, is probably the main source of the loss of nitrogen to soils.

The Nitrogen Cycle in Nature

The biological decompositions affecting the nitrogenous compounds of the soil and including the nitrogen of the atmosphere are all part of the greater nitrogen cycle that includes the life processes of animals and plants. Plants obtain their nitrogen from the soil, either from ammonium salts or nitrates or through symbiosis with nitrogen-fixing bacteria. This nitrogen is either returned to the soil in the decay of plant residues, or is utilized by animals, including human beings. But this nitrogen is also eventually returned to the soil in animal excreta or in animal remains. In the soil, the nitrogenous compounds of plant and animal remains are either ammonified and eventually nitrified, or else become changed to humic compounds, which are also, but more slowly, ammonified and nitrified. The whole nitrogen cycle may thus be represented diagrammatically.



Iron Bacteria

Another series of bacteria playing an interesting part in certain soils, consists of those which secrete hydrated ferric oxide or bog-iron ore in undrained soils, where the soil water contains ferrous bicarbonate in solution. Vinogradsky investigated four of these organisms, to whose vital processes he considered the presence of soluble ferrous salts was essential. Molisch, however, regards the secretion of ferric hydrate as, in a sense, an accidental accompaniment of their growth, much as the separation of large quantities of silica, so characteristic of the straw of cereals, is unessential to their development. It has already been noted that these iron earths do not form in soils containing calcium carbonate, which seems to prevent the formation of any soluble ferrous compounds.

Sulphur Bacteria

Just as nitrogenous compounds are broken down by microbiological processes in the soil to yield nitrates, sulphur compounds are changed to sulphates by certain groups of bacteria. These processes are all essentially oxidations, with sulphuric acid as their end-point. The sulphuric acid formed reacts with calcium carbonate or with the exchangeable calcium of the soil to give calcium sulphate. The substances thus oxidized include (1) complex organic sulphur compounds, (2) sulphides, e.g. ferrous sulphide, and (3) elementary sulphur. Sulphofication, as we may term the process, involves the production of acid, and it is therefore possible to correct excessive alkalinity by adding sulphur to the soil. Sulphur dressings have in fact been used successfully in the reclamation of alkaline soils. They have been used also in certain cases where potatoes have suffered from a kind of scab, associated with alkaline conditions in the soil. The added sulphur is oxidized by the action of the sulphur bacteria and the resulting sulphuric acid corrects the excessive alkalinity.

Under conditions of defective aerations, as in waterlogged soils, reduction of sulphates to sulphides can take place.

Sulphides are also produced in the decomposition of organic sulphur compounds under such conditions. Whilst these decompositions are mainly biological, it is probable that purely chemical processes may also play a part, and the same is true for the oxidative processes resulting in the formation of sulphates.

Waterlogged soils often contain appreciable proportions of ferrous sulphide. This is evident in many estuarine muds, which have a bluish-grey colour and smell strongly of sulphuretted hydrogen. When they are drained the sulphide is gradually oxidized and, unless calcium carbonate is present, the soil becomes very acid. Both the original sulphides and the sulphuric acid produced by their biological oxidation are harmful to plant growth and, until the sulphides are completely oxidized and the sulphuric acids either neutralized or removed by drainage, satisfactory crops cannot be grown.

Fungi of Importance in the Soil

Allusion has already been made to the fact that a large number of fungi inhabit the soil—*Penicillium*, *Mucor*, *Trichoderma*, *Spicaria*, etc., *Cladosporium*, *Cladothrix*, and various wild yeasts, *Monilia*, etc.—all of which aid in breaking down the organic matter. Many of these fungi possess the power of attacking ammonium salts applied as manure, withdrawing the ammonia and setting free the acid. To this action is due the acidity produced by the long-continued use of ammonium salts as manure, as seen on the experimental plots at Rothamsted and Woburn. At Woburn the soil is light and sandy, containing but little lime, and the application of ammonium salts containing 50 lbs. ammonia per acre

	Ammonium Salts only.	Minerals + Ammonium Salts.
With no Lime . . .	5·6	12·3
With 2 tons Lime, applied Nov. 1897	28·9	33·7

every season for twenty-four years, has rendered the land practically incapable of carrying the crops. A moderate dressing of lime, however, restores the fertility. The crops in 1900 on the barley plots are shown in the table on p. 205.

The soil had become acid to litmus paper where the lime had not been used : it is interesting to note that though barley would not grow, oats flourished freely on this sour soil. There are, however, two special organisms which merit further consideration—the fungus which clothes the finer rootlets of many classes of plants, forming mycorhiza, and the slime fungus, or *Plasmodiophora* which causes the disease known as " finger-and-toe " or " club " in turnips and other cruciferous plants.

Mycorhiza

The term " mycorhiza " is applied to the symbiotic combination of the filaments of certain fungi, whose complete development has not in all cases been observed, with the finest rootlets of certain plants. Sometimes the fungus forms a sort of cap on the exterior of the short rootlets, which are generally without root-hairs ; in other cases it penetrates the cortical tissue of the root itself, which may also be furnished with root-hairs. According to the researches of Frank, the fungus of the mycorhiza lives in symbiosis with the higher plant, attacking the humus and also the mineral resources of the soil, and passing on the food thus obtained to the host plant. In some few cases the host plant possesses no green assimilating leaves, and is wholly dependent upon its mycorhiza to obtain its necessary carbon from the humus. Such a case is seen in the *Neottia Nidus avis*, or Birds' Nest Orchis, to be found chiefly amongst beech underwood in this country.

More generally, the host plant is capable of nutrition in the ordinary way when growing in media in which nutrient salts are abundant, but becomes mycotrophic in soils and situations unfavourable to the production of directly absorbable food—as, for example, in heaths and moors, where the soil is almost wholly humus, or beneath the shade of trees, where nitrates are rarely found and where illumination is insufficient for much assimilation. Later researches, particularly those of Stahl, have shown that the symbiosis of mycorhiza, instead of being a phenomenon restricted to a few species, is widely diffused among many classes of plants, and is indeed causally connected with other facts of wide general importance in plant nutrition. It has already been indicated that the cultivated plants give off considerable quantities of water by transpiration ; the form and arrangement of their leaves are adapted to expose a large evaporating surface, the root is well developed and provided with root-hairs to keep up the supply of water to the plant. There are, however, a number of plants in which transpiration is much less active, and the leaf area is restricted or otherwise arranged to diminish the loss of water, so that the proportion previously stated as existing between the dry matter produced and the water passing through the plants is greatly diminished. A diminished supply of water to the root would, however, necessitate a loss of nutriment to the plant, as nutrient materials to some extent must enter the plant with the transpiration water. Stahl has shown that, in general, these plants with a small transpiration activity are furnished with mycorhiza, by means of which they obtain food of all kinds from the soil ; whereas, on the contrary, the plants like the cereals, the cruciferous and leguminous plants, Solanaceæ, etc., which give off water freely are never associated with mycorhiza. Many of the conifers and heaths which grow on dry soils show this correlation of a low evaporation and restricted leaf development with a root-system furnished with mycorhiza.

Another interesting generalization has also been brought into line with the above facts by the observations of Stahl that the mycotrophic plants with a feeble transpiration do not store starch in their leaves, but contain instead considerable quantities of soluble carbohydrates, chiefly glucose. In normal plants, though sugar is the first tangible result of assimilation, it is rapidly removed from the sphere of action by being converted into starch, such withdrawal of the product of the reaction being necessary if a rapid rate of assimilation is to be maintained. Should, however, sugar accumulate in the cells, the concentration of the cell sap is increased, so that it parts with its water by transpiration less readily. Though many exceptions can be observed, there seems to be a very general association of the development of mycorhiza with a diminished transpiration and the absence of starch from the leaf, especially among plants like the orchids, lilies, iris, etc., which often grow in dry or shady situations, such plants being further distinguishable by a shiny, glossy leaf surface. Stahl has again shown that the average proportion of ash to dry matter in the leaf is lower for mycotrophic than for normal plants ; the former grow, as a rule, in situations containing but little mineral salts, particularly in humic soils, where, in addition, the plant is put into competition for whatever nutriment may be present with the mycelia of fungi, which everywhere traverse humus in its natural state. By direct experiment, it has been shown that normal plants grown in humus develop better when the humus is previously sterilized by long exposure to chloroform vapour than when it is in its fresh condition, full of living mycelia competing successfully for the nutriment. The absence in the leaf of calcium oxalate and of nitrates is particularly characteristic of mycotrophic plants.

Stahl concludes that symbiosis between the roots of plants and the mycelia of fungi is a very general phenomenon, especially characteristic of plants growing in soils subject to drought, or poor in mineral salts, or rich in humus. These mycotrophic plants are generally of slow growth, possess a feeble transpiration, and limited root development ; their leaves rarely contain starch ; they are also characterized by containing a comparatively small proportion of mineral salts, among which calcium oxalate and nitrate are notably absent.

To the mycorhiza associated with plants of the genus *Erica* the power of fixing atmospheric nitrogen has been attributed, but the question still requires further investigation. In this group Rayner has shown that the mycorhiza fungus is carried in the seed-coat and is essential to germination. On plants growing in soils rich in humus mycorhiza is abundant, but it is poorly developed and sometimes absent from the roots of plants growing in dry, sandy soils poor in humus.

The existence of mycotrophy has certain interesting applications in practice; there are many plants which can only be cultivated with difficulty in gardens; for example, some of the orchids, ericas, lilies, and others, generally plants which must be grown in leaf-mould, peat, or other material rich in humus. Yet humus alone is not always sufficient for the purpose—the peat or leaf-mould has often to be obtained from a particular place; other materials, though equally rich in humus and possessing similar mechanical properties, prove quite unsuitable. It is easy to surmise that this effect, confined in the main to mycotrophic plants and humic soils, may easily be due to the absence of the proper fungus from the soils found to be unsuitable.

It has also been shown that the difficulty usually experienced in raising seedlings of exotic orchids, which die off in great number just after they have germinated, may, to a large extent, be obviated by mixing with the medium in which the seeds are sown a little of the material in which the parent plants are growing. The young seedling is found to develop mycorhiza at a very early stage, and only then will grow properly. It has been found possible to make artificial cultures of the mycorhiza associated with particular genera of orchids, and by using them as media on which to germinate the orchid seeds, to obtain as large a population of viable seedlings as occurs with seeds of normal plants. In view of the large number of plants of various species that have been found to be associated with mycorhiza it is impossible to make any general statement defining the relationship between fungus and host. In many cases the mycorhiza would appear to be parasitic and of no direct service to the host—indeed it may become harmful if other conditions should check growth. But with the orchids, the Ericaceæ, and certain conifers, the relationship is probably obligate and necessary to the development of the higher plant. Even then the dependence of the host plant on the fungus may only exist during germination and the earlier stages of growth. With mature plants in nature the symbiosis is beneficial, enabling the host to obtain nitrogen otherwise unavailable, though it can grow freely under proper conditions of nutrition.

“ Finger-and-Toe ”

On many soils, particularly those of a sandy nature, the turnip crop is often almost wholly destroyed by the disease known as “ finger-and-toe,” “ club-root,” or “ anbury.” Cabbages and other cruciferous crops are equally attacked ; so much so, that in gardens which have become infected it is practically impossible to raise crops of this nature. The disease is caused by an organism, *Plasmodiophora brassicæ,* belonging to the slime fungi and forming spores which may remain dormant in the soil for some time, certainly for two or three years. It has long been known that the best remedy against “ finger-and-toe ” consists in the application of lime ; and as far back as 1859, Voelcker showed that soils on which this disease is prevalent are deficient in lime ; and in many cases in potash also. Later researches have only served to emphasize the fact that the disease is associated with soils of an acid reaction, in which calcium carbonate is wanting, or present in very small proportions. The fungus, as is generally the case with fungi, refuses to grow in a neutral or slightly alkaline medium, and the only way to get rid of the infection in the land is to restore its neutrality by repeated dressings of lime. At the same time, the land should be rested as long as possible from cruciferous crops ; uneaten fragments of diseased turnips, etc., should not be allowed to go into the dung, or if they do, the dung should be used on the grass land. Manures, again, which remove calcium carbonate from the soil, like sulphate of ammonia or acid manures like superphosphate, should not be employed ; neutral or basic phosphates, with sulphate of potash on sandy soils, should be employed instead.

Whenever a turnip crop is seen to be infected with “ finger-and-toe ” the land should be well dressed with 3 or 4 tons per acre of quicklime immediately the crop has been removed ;

as long an interval as possible should be given before again taking a cruciferous crop, substituting, for example, mangolds for turnips in the next rotation ; every effort should be made to destroy cruciferous weeds like charlock ; turnip-fed dung should not be applied, and another dressing of finely divided quicklime should be put on for the crop preceding the sowing of the new turnip crop.

CHAPTER IX

FERTILITY AND STERILITY OF SOILS

Fertility and Condition—Factors determining Fertility—Causes of Low Productivity : Defective Moisture Conditions : Sourness—Crop Failures—Trace Elements—Presence of Injurious Constituents—Salinity and Alkalinity—Amendments of the Soil : Marling and Claying ; Paring and Burning ; Liming and Chalking ; Warping—Reclamation of Peats, Heaths, and other Rough Grazings.

IN discussing the question of fertility, a difficulty crops up at the outset in the definition of the term " fertility " : we are dealing with something intangible and dependent upon so many varying factors that it becomes a matter of judgement and experience rather than of scientific measurement. We have to distinguish between the fertility proper, " the inherent capabilities of the soil," to use the language of the old Agricultural Holdings Act, which is the property of the landlord, and for which the tenant pays rent ; and the " condition " or " cumulative fertility," the more temporary value, which is made or marred by the tenant. Though in the main it is easy to feel the distinction, it is often difficult, if not impossible, to draw a line of demarcation between them. Clearly the farmer in a new country on virgin soil is dependent wholly on the inherent fertility of the land, but with much of the land in this country it is hard to say how far its value is inherent, or due to long-continued cultivation. When a tenant by many years of skilful management makes a good pasture, the improvement is rightly credited to him, as fertility which he has accumulated : the next tenant must regard the same pasture as part of the inherent capacity of the soil. Again, a farmer working on the old four-course rotation, selling only corn and meat and purchasing neither feeding stuffs nor manures, is dependent on the fertility of the soil : another farmer, carrying on an agricultural business such as market gardening or hop-growing, and putting more into the land every year as manure than he takes out as crop, is only using the land as he would a building, as a tool in a manufacturing process.

Fertility proper is by no means a wholly chemical question, dependent upon the amount of plant food the soil contains ; in many cases the physical conditions which regulate the supply of air and water to the plant, and as a corollary, the bacterial life, are far more potent in producing a fertile soil than the mere amount of nutrient material it contains. Especially is this the case in an old settled country like England, where manure is relatively cheap and abundant ; here a fertile soil is often one that is not rich in itself, but one that is responsive to, and makes the most of, the manure applied. Clay soils are not uncommon which show on analysis high proportions of nitrogen compounds and potash, and again no particular deficiency in phosphoric acid, but from their closeness of texture they offer such resistance to the movements of both air and water as to carry very poor crops. Some light soils again, such as those on the chalk, would be regarded on analysis as rich, but they are made so persistently dry by the natural drainage, that only in a wet season do they keep the crop sufficiently supplied with water for a large crop production. On nearly all poor soils it is impossible to effect much improvement by the use of manures alone, in fact, manuring will not turn bad into good land, the conditions limiting the amount of crop being other than the food supply. Of course, by the continued incorporation of humus into a light soil, its physical texture may be improved at the same time as its richness, until it becomes sufficiently retentive of water for the needs of an ordinary crop, just as a heavy soil may be lightened by similar additions of humus. It has already been mentioned that many subsoils, especially of the heavier loams and clays, are extremely infertile when brought to the surface, even though they may possess a fair proportion of phosphoric acid and potash and be artificially supplied with nitric nitrogen. Some of this effect is due to texture and structure, part to the very scanty bacterial flora they possess ; but it is to be noted that in arid climates the subsoils, which are not more fine-grained than the surface soils, do not always show the same infertility when brought to the surface. *Per contra*, some acid subsoils in South Africa and Australia are extremely infertile from their great deficiency in phosphoric acid, which has been wholly concentrated in the surface soil by vegetation, and even there is comparatively deficient.

The soils that show the greatest fertility are, as a rule, soils derived from transported material, uniform and fine-grained in texture, but with particles of a coarser order than clay predominating, so that, whilst moving water easily by capillarity, they are freely traversed by air and percolating water. As a rule, they also contain an appreciable amount of organic matter at all depths. We have nothing comparable with the typical " black soils " of the North American prairies or the Russian steppes, which contain very large proportions of organic matter to considerable depths in the subsoil : as, for example, a soil from Winnipeg that contained 0·428, 0·327, 0·158, and 0·107 per cent. of nitrogen in the top 4 feet of soil successively. Many of these deep rich soils appear to be derived from wind-borne material : in all cases they are of very uniform texture, and represent the accumulated residues of ages of previous vegetation in a form that is capable of decay and nitrification so as to become available for subsequent crops. In a peat bog there is equally an accumulation of organic matter and nitrogen, but the mass is infertile because of the acid character of the humus (which causes the absence of the valuable bacteria, such as those fixing nitrogen and nitrifying ammonia), the deficiency of mineral plant foods, and the bad mechanical condition which affects the supply of air and water. In the main, then, a fertile soil is one rich in the débris of previous vegetation, one which possesses a very uniform texture, adapted to satisfy the needs of the plant for air and water. Mechanical texture is of fundamental importance : in this country many soils owe their value to this property alone ; for example, the Thanet Sand formation in East Kent (a very fine-grained sand or silt), though it contains but little plant food, yet carries some of the best fruit and hop plantations in the kingdom, and farms on it command a high rent. Even more famous examples are the silt soils of Boston and Wisbech on the seaward side of the Fens, or the famous red soils of Dunbar. Both are light and easy working and show no great richness from the chemical point of view except as a result of continuous and heavy manuring. But they are happily tempered and of the right texture for the free movement of water in the soil, with the result that they respond to good cultivation and carry some of the best crops in the country.

Condition

The question of condition has equally its chemical and its mechanical side ; it is well known that on any but the lightest soils continued cultivation, using the practices of good husbandry, makes the texture better and renders it easier to obtain a seed-bed. On clay soils the effects of bad management are very persistent ; any ploughing, rolling, or trampling when the soil is wet will so temper the clay that the effect is palpable until the land has been fallowed again or even laid down to grass. Once protected from the action of frost, stiff soil which has been worked when at all wet never seems able to recover its texture, as may be seen by examining the clods that are to be found on digging up an old post, the result of the trampling when the post was originally put in. The dependence of " condition " upon the maintenance of a good texture is to be seen in the custom of regarding wheat as an exhausting crop, whereas few of our farm crops withdraw less plant food from the soil. The popular opinion really represents the fact that the wheat crop occupies the land for nearly a year, during which period the soil receives little or no cultivation, and so falls into a poor state of tilth.

From the chemical side " condition " means the accumulation within the soil of compounds that will by normal decay yield sufficient available plant food for the requirements of an ordinary crop, e.g., of organic compounds of nitrogen that readily nitrify, of phosphoric acid and potash compounds that readily become " available " for the plant. A soil in good condition must also contain an abundant flora of the ammonia-making and nitrifying bacteria ; indeed high condition is roughly indicated by the content of the soil in these bacteria and the rate at which it will produce nitrates.

The condition of land cannot be restored all at once by manuring ; the residues of manures left in the soil after the first season are slow-acting, i.e., only a small proportion of them becomes available year by year, so that there must be a considerable accumulation of such residues before the proportion becoming available during the period of growth is sufficient for the crop. On the other hand, the condition can be only too easily destroyed by cropping without manure ; the unexhausted residue left after each year is successively less and less active, the crop falls off rapidly, till at last a sort of stationary condition is reached, and the somewhat inert materials, still left in large quantity, liberate year by year a fairly constant proportion of active plant food. The wheat plots at Rothamsted that have been cropped without manure since 1852 illustrate this point. From the following table, giving the average yield in cwt. dressed grain per acre in each decade, it appears that, after an initial decline, the yield has shown no very marked downward tendency. Indeed, in the last recorded period (1932–9) the yield has shown a recovery over the preceding decades.

1852–61	1862–71	1872–81	1882–91	1892–01	1902–11	1912–21	1922–31	1932–39
8·9	8·2	5·7	6·9	7·1	6·4	5·3	5·5	7·2

Condition may best be regarded as a state of equilibrium when the land will continue to give a good return in crop for the manure applied ; as a rule, the crop recovered by no means contains the whole of the material applied as manure, a certain portion being retained in a comparatively inactive form or else lost in the drainage waters. With the land in condition the remaining nutrient material required for a good crop is supplied by the dormant residues in the soil which have become active : at the same time, these reserves are protected from depletion by renewal from the inactive portions of the current manuring. On the other hand, if the land is in poor condition the crop gets little or no assistance from the soil, but is grown from the active part only of the manure : the rest of it accumulates and begins to build up condition, which, however, does not tell on the yield for some time. As a practical consequence, it is noticed that only land in good condition gives a paying return year after year for the application of manure : yet if the experiment be made of omitting the manure on a portion of the land for one year, there is little corresponding reduction of yield, as though the manure went to keep up the " condition," and the crop was grown out of that rather than from the manure applied.

" Condition " is one of the most valuable of the properties of the soil to the cultivator ; as it may be destroyed or created by the tenant during his occupation of the land, it should be as far as possible a tenant's asset, to be bought by him on entry and valued to him on leaving. The difficulty which even an experienced man finds in putting a value on so intangible an item makes it almost impossible to assess the condition of a farm, but it is desirable in every way that the outgoing tenant should be encouraged to maintain the condition of his farm by giving him due compensation for the unexhausted value both of manures and foods used in the latter years of his tenancy.

Factors determining Fertility

Plant growth is controlled by a number of factors, or groups of factors. These are :

(1) A supply of carbon dioxide in the air from which the plant elaborates organic matter in photosynthesis.

(2) Light, as a source of energy for the process of photosynthesis.

(3) Suitable temperature. There is for the growth of every species of plant a minimum temperature, below which growth ceases, a maximum temperature, above which growth ceases, and an optimum at which growth takes place most rapidly.

(4) Moisture supply. For every part by weight of dry matter formed in plant growth, some hundreds of parts by weight of water are required. The water is required to make good losses by transpiration, and as a solvent for the plant food taken in by the roots.

(5) Air supply. Plant roots require oxygen for respiration and in the absence of oxygen cannot develop. The root system therefore only occupies those horizons of the soil to which air has access.

(6) Plant food. By this is understood all those elements absorbed from the soil through the roots of plants. Nitrogen, phosphorus, sulphur, calcium, magnesium, potassium, and iron have long been known to be essential for growth, and during recent years the list of essential elements has been considerably extended, and includes zinc, copper, boron, manganese, iodine, and possibly nickel. The list is continually being added to.

(7) Absence of injurious constituents. These may be salts, such as sodium chloride or sulphate ; acids such as sulphuric acid ; alkaline substances, such as sodium carbonate ; or poisonous metallic compounds, such as salts of copper, lead, zinc, or nickel. Injurious substances may also be present in the air in industrial regions ; the commonest injurious constituent in the air is sulphuric acid, but metallic fumes and

dusts may also occur, as, for example, in the neighbourhood of nickel and zinc works.

(8) Absence of excessive competition. This means freedom from the competition of weeds. One of the principal objects of the farmer's cultivations is the suppression of weeds.

(9) Root hold. The soil must be sufficiently stable to give an anchorage to plant roots. Blowing sands are defective in this respect.

(10) Other factors. This heading includes the unknown or little known factors in plant growth, including the presence of possible growth-promoting substances, known as auxins.

For optimum growth of any particular crop, all these factors must be at optimum, and the optima may not be the same for all crops. In any given soil and situation, plant growth will be limited by that factor, or group of factors, which operates most unfavourably. For example, moisture supply may be the limiting factor, as it is in fact in arid regions. If so, it will not be possible to obtain maximum crops by increasing the supply of plant food in the soil. This is in agreement with experience in dry countries that fertilizers have little effect on crop yields compared with the effect of water supply in rainfall or irrigation. The art of soil improvement is based on discovering the limiting factor or factors, and in modifying them in a direction favourable to plant growth.

If the limiting factor has been discovered and rectified, it will probably be found that a second factor will now be limiting plant growth. For example, if plant growth on a given soil has been limited by drought and this has been rectified by irrigation, there will be an increase in crop yields, but a limit may be set to this increase by the deficiency of a plant nutrient, e.g. phosphorus. This must be remedied before further increase can be obtained.

When all efforts have been made to remedy obviously limiting factors, two factors remain outside the control of the farmer. These are light and carbon dioxide supply. These, however, permit a fairly high " ceiling " of production. Temperature is also, except to a limited extent, outside human control. It can be controlled in glasshouses, but in the fields, the farmer can do little more than increase the temperature of his soil by a degree or two through drainage and cultivation.

We have thus considerably enlarged our conception of soil fertility to mean the optimal operation of all the factors involved in plant growth, and not simply an abundant supply of plant food attained through liberal manuring. It should be noted, however, that the term fertility, like many other terms used in the study of the soil, is used in more than one sense, and, in addition to meaning the favourable operation of all factors in plant growth, is also used to denote an abundant supply of plant food. Thus, in the literature, studies on soil fertility generally mean investigations of the plant nutrient status of soils. We may distinguish a third sense in which the term is used, namely the ability to give a good response to the efforts of the farmer. For example, there are soils derived from the Bunter Sandstone which are naturally of low productivity, but which in the hands of skilful farmers can be brought to a high state of productivity. The same may be said of the sandy soils of the Biggleswade district of Bedfordshire, which are used for market gardening. Fertility in this sense, the sense in which the word is generally used by economists, means responsiveness to the efforts of the cultivator.

Fertility, in whatever sense the term is used, is not entirely dependent on the soil. It depends also on the climate, which determines the temperature conditions and the supply of water in the rainfall. A soil that would grow bumper crops in the lowlands would yield very poorly if located 3,000 feet up in the mountains or in the Sahara desert. Apart from the necessity of a suitable climate for productivity, the crops grown must be adapted to the climate. Failure to grow maize satisfactorily is no reflection on the fertility of an English soil, because the crop is not suited to our climate. Crops must also be adapted to the soil. We must not expect to grow good wheat and beans on a light sandy soil that might be ideal for potatoes or barley. We can assess the fertility of the soil only when we consider its performance with the crops most suited to the climate and to the soil itself.

Certain limitations must be recognized. When everything has been done in adapting husbandry to climate and soil, and when all measures have been taken to adapt the soil to profitable use, there are soils that cannot be other than of moderate or low productivity. By no effort of human skill can the thin, rocky soils of our uplands, or the blowing sands of our coastal districts be made to bear heavy crops or carry rich grass herbage.

Under a favourable climate, we shall expect our highest productivity in lowland areas, with fairly level or gently rolling or sloping topography, and deep well-drained soils, neither too heavy nor too light in texture. Such soils repay the efforts of the farmer and are generally rich in plant food from generations of good management and manuring. Much can still be done to raise the productivity of our second-class lands. In many cases, drainage or liming would at once lift them into the first class. The fact that a soil is at present producing little does not mean that it is an inherently poor soil.

Soil fertility has sometimes been likened to a chain whose strength is that of its weakest link. To strengthen the chain, the weakest link must be strengthened, but when this has been done, its strength is that of the second weakest link, and so on. The analogy of the chain must not, however, be pushed too far. A chain can only be strengthened by strengthening the weakest link, whereas with the soil, some increase in plant growth may be obtained by improving any one of perhaps half a dozen factors. A soil suffering from acute phosphorus starvation, may yet give some response for nitrogenous manuring. This response would, however, be greater, if the phosphate deficiency had been remedied.

Where it is possible to express factors numerically, it is of interest to study crop responses to increases of a given factor.

If the yield of crop be plotted against the amount of any plant growth factor, curves of the general type shown in Fig. 19 are obtained The general law is that that rate of increase per unit dose of fertilizer, or any other soil amendment capable of measurement, is proportional to the difference between the actual yield and the maximum yield. For example, if we take a hypothetical soil that is satisfactory for plant growth in every respect except that it is devoid of nitrogen, by successively increasing the nitrogen supply the yield will eventually reach its maximum. In practice, of course, before this theoretical maximum would be reached, the adverse effect of an excessive concentration of salt in the soil would be manifest. If we take as our unit of nitrogen the amount required to give 50 per cent. of the maximum yield, then 2 units will give 75 per cent., 3 units 87·5 per cent., 4 units 93·75 per cent., and so on. This is shown in curve I in the diagram. If some other factor is operating at less than optimum, for example permitting only 50 per cent. of the full yield, then the response curve would be as in curve II.

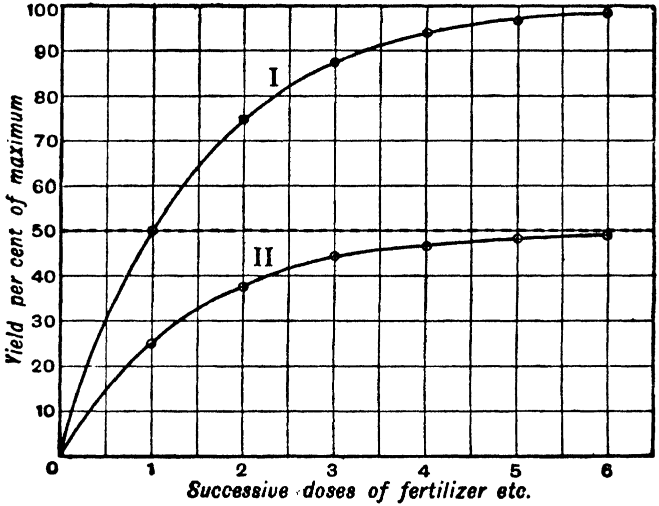


FIG. 19.—Response Curves.

These curves are to a large extent ideal and theoretical. In practice, results would be found to diverge considerably from the simple law above enunciated. It is, however, safe to assume that the response to any given factor gradually falls off as the yield is raised. A low response to an increment of any plant growth factor may mean either that the factor is already near the optimum, which would be the case in the upper part of the curves in Fig. 19, or it may mean that other factors are limiting the maximum yield.

An actual example of a response curve is furnished by the often quoted results of different levels of nitrogenous manuring on the yield of wheat in the Broadbalk Field at Rothamsted. These are given in the following table:—

AVERAGE YIELDS OF WHEAT (1852–64) ON CERTAIN PLOTS AT BROADBALK, ROTHAMSTED

Manures per acre.	Yield of grain in bushels per acre.
Minerals alone	18·3
„ + 43 lb. N. as ammonium salts .	28·6
„ + 86 lb. „ „ „ .	37·1
„ + 129 lb. „ „ „ .	39·0
„ + 172 lb. „ „ „ .	39·5

If these results are plotted on a curve as in Fig. 20 the general similarity to the upper part of the curves in Fig. 19 is seen. The curve does not start from zero, because some nitrogen is already present in the soil. By extrapolation at the lower end, we may conjecture that, even with no nitrogenous manuring, there is in the soil something of the order of 45 lb. nitrogen per acre already available for plant growth. The curve also suggests that the maximum possible yield under the conditions of the experiment is not much more than 40 bushels. To increase the yield above this, some other factor, such as water supply, would have to be improved.

By discovering and successively remedying limiting factors there is no doubt that on any given soil, crop yields could be greatly increased. Economic considerations, however, soon impose a limit to such improvements. From the form of the response curves it is evident that each successive dose of any particular factor gives a smaller return. In the figures quoted in the last table it is seen that the first dose of nitrogen gives an increase of 10·3 bushels, the second dose, 8·5 bushels, the third dose, 1·9 bushels, and the fourth dose only 0·5 bushels. This falling off in response may be seen in all types of improvement. To what point it pays to push production, depends on costs of production and on crop prices. Prices are entirely outside the farmer's control, whilst costs of production are only partly within his control.

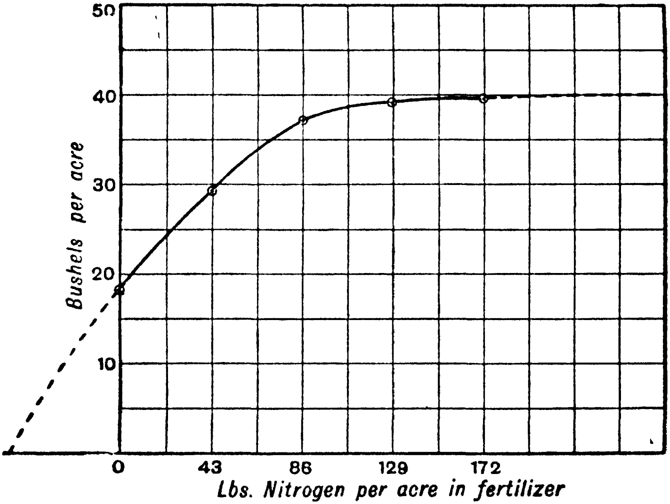


FIG. 20.—Yields of Wheat at Different Levels of Nitrogenous Manuring.

Causes of Low Productivity

We have hitherto tried to understand what is meant by fertility. It has been customary in writing of the soil to contrast sterility with fertility. Yet few soils can be described as sterile, and in practice we are more concerned with soils that, for one or more reasons, do not yield as satisfactory crops or grass as might be expected from the climate in which they occur. At the outset, we may distinguish between generally low productivity and the special conditions resulting in the failure or partial failure of crops on otherwise productive soils. These are best considered under the heading of crop failures.

Considering, then, the problem of generally low productivity, we must note that everything is relative and that there is no hard and fast line between a productive and an unproductive soil. There are, in fact, all gradations from the most fertile to the most infertile soils.

The most frequent cause of infertility or defective productivity is an unsatisfactory moisture-air status in the soil. This may mean either deficiency of moisture or deficiency of air. If we consider the most obvious instances of low productivity, namely, the soil of waste and uncultivated lands, it will almost invariably be found that deficiency of moisture on the one hand or excess of moisture, implying deficiency of air, on the other is the limiting factor. If we go from a fertile lowland up through the higher slopes towards the open mountain we find a general decline in productivity as we ascend, until finally we reach the limit of the cultivated land. Beyond this limit we have the rough grazings of the intakes, and finally the open mountain. By improved methods some of these lands lying above the present limits of cultivation can be improved, and many thousands of acres of our marginal lands have been reclaimed and made to carry crops and leys. Although the grazings thus obtained represent a considerable increase in stock-carrying capacity over the rough grazings from which they were formed, they are subject to rapid deterioration unless carefully grazed and managed. Probably the main factor in their deterioration is the occurrence of drought. The soils are generally thin, and the occasional drought that occurs even in regions of normally high rainfall has more serious consequences than would be the case on a deep lowland soil.

In the lowlands, low productivity due to moisture deficiency is seen in the soils of sandy heaths and coastal dune areas. Among cultivated soils, deficiency of moisture is most prevalent on sandy and gravelly soils, particularly where there is a coarse gravel subsoil, as in many of the river and plateau gravels of Southern England. The extent to which drought limits production depends in a large measure on the season, but on most soils, including some of the most fertile, there are periods when plant growth suffers from lack of moisture, particularly in the early stages of the growth of arable crops before their root systems have become established.

Deficiency of moisture is not confined to thin light soils. It may also occur on heavy soils which during a large part of the year suffer from excessive moisture. The effects of drought may be clearly seen on many pastures on heavy clay. This may be attributed to the shallowness of the soil and the consequent restriction of root development to the top few inches. The cracking of such soils during drought further accentuates the drying-out.

Excessive moisture is not in itself a harmful factor, but rather the deficiency of air that is associated with it. When the pore space of the soil is completely filled with water, air is completely excluded and the growth of plant roots impossible. Excessive moisture may have some unfavourable effect through rendering the soil cold and late. It also adds to the difficulties of cultivation in heavy soils.

Wetness in the soil depends partly on climate and situation and partly on the character of the soil itself. As a soil defect it is commoner in the wetter districts of the west and northwest. In drier regions it is usually confined to low-lying areas, where the regional water-table is near the surface. So far as the excess of moisture is caused by the soil itself, it is mainly found in heavy impervious soils. Clays differ considerably in this respect and the structure of the soil has an important effect. Some heavy soils are naturally well fissured and have a fairly good natural drainage. On the other hand there are soils which, judged by their mechanical analysis, are not very heavy, but which nevertheless show a compact structure in the subsoil and are consequently liable to be poorly drained, Many of the soils derived from Coal Measure shales have this undesirable character. The occurrence of a pan can also lead to defective drainage. Where this is the case, it is often possible to effect an improvement by breaking the pan with a subsoiling implement or even by the use of explosives.

Apart from the coldness and lateness associated with wetness in soils, the principal harmful effects of wetness are associated with deficient aeration. This affects the growth of plants directly by restricting the respiration of their roots. The root system of agricultural crops is, in fact, confined to the well aerated upper layers and does not extend into horizons which, either through waterlogging or through compaction, are deficiently aerated. Apart from this directly harmful effect of deficient aeration, there are also effects on the soil itself. Reducing conditions result in the formation of harmful ferrous compounds, notably ferrous sulphide. These conditions also favour the action of denitrifying bacteria, whereby nitrates are lost from the soil. Finally, the continued prevalence of defective aeration leads to the accumulation of peaty humus, and in extreme cases to the formation of peat itself.

Much of the difficulty in the reclamation of wet soils consists in the elimination of harmful compounds that have been formed under the anaerobic conditions of the original soil. Many clay soils are coloured dark blue or green by double ferrous silicates like glauconite, or by finely disseminated iron pyrites. Until these materials become oxidized to ferric hydrate, the soil remains sterile : particularly is this the case with iron pyrites, which in the form of marcasite easily oxidizes to yield both ferrous sulphate and sulphuric acid. Voelcker has recorded three instances of soil sterile through these causes : one was land reclaimed from the bed of the Haarlem Lake, which contained 0·71 per cent. of iron pyrites and 0·74 per cent of ferrous sulphate, as well as some insoluble basic sulphate of iron. Another example of land reclaimed from the sea contained 0·78 per cent. of pyrites and 1·39 per cent of ferrous sulphate. Under anaerobic conditions such as are set up in a completely waterlogged soil, the sulphates present are reduced to sulphides, and, by further reactions with the compounds of iron present, black ferrous sulphide is produced. Cultivation with a free use of lime and chalk is the best means of ameliorating such soils, which always show an acid reaction.

" *Sourness* " *in Soils*

On the chemical side, by far the commonest cause of infertility is " sourness," using this popular term to include all those defects of the soil that are remedied by lime dressings. Although " sourness " is often regarded as synonymous with acidity, it is not certain that acidity is always or even generally the immediate cause of infertility. Acidity is correlated with low base-status and it is therefore not always clear which of the two directly affects plant growth

Many workers regard acidity as the immediate cause of infertility and lists have been compiled giving critical *p*H values below which the principal crops fail to make satisfactory growth. Such figures should be received with caution. For example, sugar-beet may fail at a *p*H below 5·5 under certain conditions of soil and climate, yet under different conditions the critical *p*H may be above or below this figure. It is certain, however, that very low *p*H values, or in other words, excessive hydrogen-ion concentration in the soil moisture is harmful to plant growth. This directly harmful effect begins to operate at *p*H values below about 4·5 for most crops and is very marked below *p*H 4·0. In such cases the presence of mineral acids, usually sulphuric acid, may be inferred.

Acidity also affects the microbiological and chemical processes in the soil. Under acid conditions, the activity of the nitrifying and nitrogen-fixing bacteria is suppressed, and plant residues on decomposition give rise to raw humus instead of the mild humus of neutral soils.

Chemically, the most important effect of acidity is on the reactions affecting soil phosphorus. Whilst under neutral or alkaline conditions the stable phosphorus compounds are calcium phosphates of the apatite type, under acid conditions the less available iron and aluminium phosphates tend to be formed.

It is equally possible that the immediate cause of infertility in " sour " soils is calcium deficiency or, in more general terms, low base-status. An acid reaction is correlated with low base-status, but in soils containing much humus the *p*H value may be low and yet the content of exchangeable bases may be moderately high. On such soils, provided there is a sufficiency of lime, satisfactory crops can be grown at *p*H values that would be regarded as indicating infertility in soils of lower organic matter status.

Active and toxic aluminium has been suggested as the immediate cause of infertility in acid soils. It is undoubtedly true that the availability of aluminium increases with fall in *p*H value, but since it is impossible in ordinary soils to separate aluminium solubility from low *p*H value, it is difficult to determine which of the two is the efficient cause of infertility.

Crop Failures

It may happen that particular crops may fail or give low yields on soils that are generally of moderate or high fertility. In some cases, the failures are due to accidental causes, such as insect or fungoid attack, or to bad cultivation as, for example, when old grass is ploughed up and the furrow insufficiently consolidated in the preparation of the seed-bed.

Apart from these accidental causes, there are failures that can be attributed only to nutrient deficiencies. The most frequent cause of trouble is potash deficiency. Whilst British farmers are well aware of the value of phosphate and nitrogen, the importance of potash is not so generally realized. Where the type of farming is fairly intensive, involving the sale of crops or milk off the farm, an insufficient use of potash fertilizers can result in the depletion of the soil in potash. Dairy farms are particularly liable to develop poor potash status. Little potash was brought on to farms in the form of purchased feeding stuffs, and with the abundance of farmyard manure, the only artificial used was slag. Meanwhile potash was being lost from the farm in milk and also in the washings from the cow byres. The latter source of loss may be obviated by fitting a type of gully whereby washings can be run away, whilst the urine ordinarily flowing out can be led to the liquid manure tank.

Low potash status may result in partial or complete failures in a number of crops, notably potatoes, sugar-beet, mangold, beans, and barley.

During recent years, possibly as the accumulated result of years of one-sided manuring, magnesium deficiency has caused partial failures on certain light soils. It may be remedied by the use of dolomitic limestone, or by applications of magnesium sulphate.

Excessive use of lime on certain soils may lead to failures through lowering the availability of certain elements. The best-known examples are boron deficiency, causing failures in sugar-beet, swedes, and kale, and manganese deficiency, causing grey speck in oats and marsh spot in peas.

Failures from plant nutrient deficiencies can often be diagnosed by leaf symptoms, which are characteristic for each element and crop. In some cases the diagnosis may be made in time to take remedial measure. For example, if grey speck in oats is diagnosed in the early stages, the crop may be saved by spraying with 2 per cent. manganese sulphate solution.

Trace Elements

Whilst it is true that most soils of low productivity are poor in plant nutrients, this is generally the result of neglect rather than the primary cause of infertility. Such soils almost invariably suffer from some less remediable defect, such as excessive wetness or dryness and have been found by experience not to repay for good management and manuring. It is very exceptional to find a soil fertile in all other respects, but unproductive through deficiency in one or more of the major plant nutrients, nitrogen, phosphorus, or potash.

Of recent years considerable attention has been given to infertility in soils due to deficiencies in the so-called minor or trace elements. It was formerly supposed that the elements necessary for plan growth were carbon, hydrogen, oxygen, nitrogen, phosphorus, potassium, sulphur, calcium, magnesium and iron. This list proved to be incomplete and has been considerably extended. It is now known that among essential elements for plant growth we must certainly include manganese, boron, iodine, cobalt, copper and zinc, and further work will doubtless add to the list.

Many obscure cases of infertility in soils have been traced to deficiency in minor or trace elements. As a rule, however, minor element deficiency shows itself rather in the unsatisfactory growth of particular crops than in general infertility. It may occur in otherwise productive soils and, indeed, intensive production with its heavy drain on plant nutrients may actually accentuate the trouble.

Manganese deficiency is a fairly common cause of crop failures on certain soils and gives rise to " grey speck " in oats and " marsh spot " in peas. Mangolds, beet, potatoes, and wheat are also affected. The trouble is caused not necessarily by actual deficiency of manganese in the soil, but by a reduced availability. A high calcium status is an invariable condition. Soils where manganese deficiency symptoms occur generally have free calcium carbonate and *p*H values of 7·0 or over. On the other hand, there are many calcareous soils where manganese deficiency does not occur and it is probable that the type of organic matter present also plays a part. Some of the worst failures from manganese deficiency occur on peaty soils, but cases may also occur on other soil types. The exact mechanism whereby manganese availability is reduced is still incompletely understood. Fortunately, the control of manganese deficiency is not difficult. Spraying the crop with a dilute solution of manganese sulphate in the early stages has proved very effective. As little as 10–12 lbs. per acre in a 1 per cent. solution have been used with success.

Deficiency of *Zinc* may cause partial or complete failures. Up to the present, no well-established cases have been reported in this country.

Boron deficiency may cause a brown internal rot in potatoes, mangolds, swedes, and kale. Failures in tomatoes, tobacco, and beans have also been reported. Boron deficiency resembles manganese deficiency in being accentuated by a high lime status, but it may also occur on acid soils. In such cases it may be presumed that there is an actual deficiency of boron in the soil. Up to 20 lbs. per acre of borax may be used to control this deficiency.

Deficiency of *Copper* does not, so far as is known, lead to crop failures or depression in yields under British conditions. Copper is, however, an essential element for plant growth, and in other countries, notably in Holland, the United States, and South Australia, definite cases of failures from copper deficiency have occurred. In Holland, a type of crop failure known as " reclamation disease " is found on reclaimed peats. This has been found to be associated with copper deficiency and has been remedied by dressings of a few pounds of copper sulphate per acre. Similar cases have been reported on reclaimed peat soils in Florida and other parts of the United States.

Molybdenum deficiency has been reported from Australia. So far as is known, it does not occur in Britain.

Apart from crop failures caused by deficiencies in plant food, there is a whole group of animal diseases or nutritional derangements associated with mineral deficiencies in the grazing herbage. Instances of such deficiencies associated with lack of calcium, magnesium, or phosphorus, have long been known. During recent years, however, it has been shown that deficiencies of certain minor elements in the herbage may also cause nutritional derangements. The most striking examples are cobalt deficiency, associated with " pining," and copper deficiency, associated with " swayback " in sheep. The problem is not completely solved because the characteristic symptoms may occur also where no deficiency of copper or cobalt in the herbage and soil can be verified.

Cobalt deficiency was first encountered in New Zealand, where a characteristic wasting of stock termed Morton Mains disease or " bush sickness " occurs. It has been found in many parts of the world including Great Britain, where " pining " of sheep in certain districts of Scotland and Wales has been traced to cobalt deficiency.

There are also instances of stock ailments due to the presence of harmful trace elements. The most striking instance of this is given by the so-called " teart " pastures, which occur on the Lower Lias in Somerset and, to a lesser extent, in Gloucester and Warwick. These pastures are found to produce " scouring " in stock, particularly cows in milk and young cattle. Horses and pigs are not affected. Acid soils do not show teartness. Hay from teart pastures is comparatively harmless. It is only during recent years that the cause has been found to be the presence of molybdenum in the herbage. Administration of small doses of copper sulphate to animals has been found to give a satisfactory control.

Infertility due to Injurious Constituents

Harmful soil constituents as causes of soil infertility may be grouped under the following headings : (1) acids in the soil ; (2) poisonous metallic compounds : (3) soluble salts, including alkalis.

Infertility due to acidity has already been discussed under the heading of soil sourness. Extreme instances of infertility due to the presence of mineral acids are found in industrial regions, where large amounts of sulphuric acid are brought down in the rainfall. The damage is two-fold. In the first place, there is the accumulation of acidity in the soil, which can be remedied by a sufficient use of lime dressings. Secondly, there is the more serious direct effect of the acid fumes on vegetation. This can be readily seen in the poor growth of trees in highly industrialized districts. The only remedy would appear to lie in measures to abate the emission of acid fumes in smoke and waste gases.

Under the heading of poisonous metallic substances, we include compounds of lead, zinc, copper, and nickel. Infertility due to these is sporadic and confined to the vicinity of mine workings and smelting works. The trouble is not confined to the actual area covered by mine workings : the dust from spoil heaps can be carried by the wind for many miles and spread over agricultural land, which is thus rendered more or less infertile, depending upon the distance from the source and the direction of the prevailing wind. Fumes from smelting works can also affect a considerable area.

The damage due to metallic poisons can be offset to a large extent by heavy liming, i.e. up to the point at which there is free carbonate present in the soil. A good instance of the effect of lime is seen at Parys Mountain in Anglesey. This was formerly one of the largest copper mines in Europe, but is now a scene of desolation and sterility. Near ruined buildings and walls, however, there is an abundant growth of weeds and grass. This may be attributed to the effect of the mortar rubbish.

Salinity and Alkalinity

Sterility caused by salt is sometimes to be seen in this country in the marshes near the sea : more often a " salting," even where the sea has regular access, is clothed with vegetation which is able to endure very considerable proportions of salt. Most farm crops will grow in soil containing 0·25 per cent. of salt, and in the reclaiming of the old sea lake of Aboukir in Egypt, it was found that grasses would grow freely where there was still as much as 1 per cent. of salt in the soil, and a scrubby winter crop of barley was grown on soil containing more than 1½ per cent. " With 2 per cent. of salt in the soil, a fair crop of dineba (grass), 2 feet high, can be grown ; with 1 per cent. it attains its full height of 4 feet, and sells as a standing crop at from 20s. to 25s. per acre. For ' berseem,' or clover, the percentage of salt should not exceed ½, and about the same for ' sabaini (quick-growing or seventy-day) rice.' " Much, however, depends upon the relations between water supply and evaporation, as to the amount of salt in a soil which would be tolerable to vegetation.

In arid climates the rainfall is often insufficient to produce percolation through the soil and subsoil into the underground water system ; in consequence, salts tend to accumulate in the subsoil, and may be brought to the surface by capillary rise so as to cause almost entire sterility. Such bad lands are known in America as " alkali soils," but they are well known in India and in Egypt, and indeed are common to all countries possessing a small rainfall and great evaporation. Saline soils, particularly at the end of the dry season, show an actual white efflorescence of salts at the surface ; all vegetation is destroyed, except one or two plants which seem tolerant of large quantities of saline matter, such as " greasewood," *Sarcobatus*, sp., or the Australian " saltbushes," *Atriplex semibaccatum*, etc. In some cases, the alkali is chiefly located at a slight depth in the soil, and only effloresces on spots a little below the general level, where the subsoil water comes to the surface. A heavy rainfall may be followed by a rise of salts, because a connexion is then established between the saline subsoil water and the evaporating surface, whereupon a continuous capillary rise of salts takes place, followed by their crystallization at the surface. *Per contra*, the establishment of a soil mulch, and shading the ground with a crop, so that evaporation only takes place through the leaves, will aid in keeping the salts down. The composition of the salts varies ; as a rule, sodium chloride predominates, with some sulphates of sodium, magnesium, and calcium, in which case the material is known as " white alkali." In alkaline soils, the soluble material is really alkaline, containing sodium carbonate and bicarbonate ; the saline solution then dissolves some of the humus present in the soil, and also causes the resolution of the clay material into its finest particles, so that the soil forms an intensely hard black pan when dry, which is known as " black alkali." The carbonates are far more injurious to vegetation than the neutral salts ; few plants can bear as much as 0·1 per cent. of sodium carbonate, but are tolerant of 0·5 to 1 per cent. of the other salts. Because of the mode of their formation alkali soils are also characterized by the very complete replacement of bases like calcium and magnesium in the soil colloids by sodium, with the result that the soils with even a normal proportion of clay become almost unworkable.

Though the alkali salts are sometimes chiefly sulphates, more commonly sodium chloride is the main constituent,

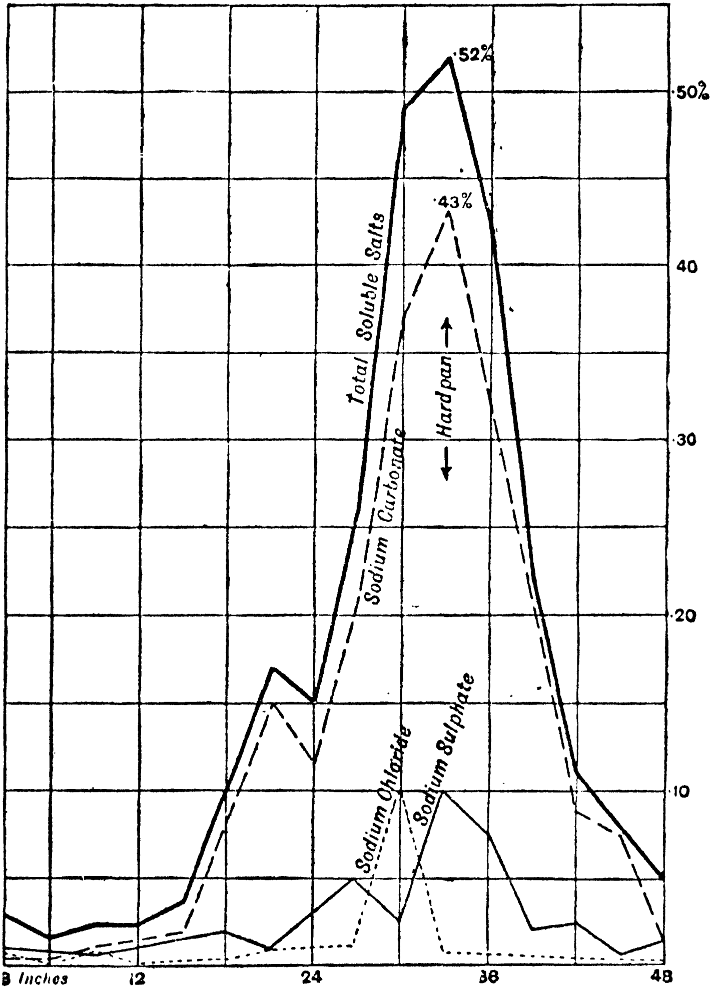


FIG. 21.—Nature and Distribution of Alkali Salts (Hilgard).

together with the products of its action in mass upon calcium carbonate and sulphate. The diagram (Fig. 21), due to Hilgard, shows the distribution with depth of alkali salts in this type of soil at Tulare, California ; the greatest accumulation of salts takes place at a depth of 30 inches, the point to which the annual rainfall penetrates. One of the most difficult features presented by the cultivation of land in arid regions where " alkali " occurs in the soil, comes from the tendency of the sterile spots to spread and the salts to be brought to the surface as soon as irrigation water is employed, for without irrigation agriculture is hardly possible. Many districts, which at first carried good crops and were even laid down in fruit or vines, have been ruined through the rise of alkali to the surface brought about by irrigation ; in fact, in all these arid regions it becomes exceedingly dangerous to raise the water-table in the land anywhere near the surface, because capillarity then causes a rise of the salt-charged water, and evaporation concentrates it on the top. Just as some of the worst alkali land occurs where rain falling upon the surrounding mountains finds its way by seepage through the subsoil rich in salts and then rises to the surface in the dry basin areas below, so the introduction of irrigation canals pouring large volumes of water upon the land may equally establish the capillary connexion between the subsoil salts and the surface. The following extract from Bulletin No. 14, U.S. Dept. of Agric., Div. of Soils, dealing with alkali soils in the Yellowstone Valley, shows the evil effects of incautious irrigation :

" Irrigation has been practised for twelve or fifteen years. The water for the main ditch supplying the valley is taken out of the river nearly 40 miles above the town of Billings. When the country was first settled, and indeed above the ditch at the present time, the depth to standing water in the wells was from 20 to 50 feet, and there were no signs of alkali on the surface of the ground. Under the common practice or irrigation, however, an excessive amount of water has been applied to the land, and seepage waters have accumulated to such a degree that water is now secured in wells at a depth of from 3 to 10 feet in the irrigated district, while many once fertile tracts on the lower levels are already flooded, and alkali has accumulated on them to such an extent that they are mere bogs and swamps and alkali flats, and the once fertile lands are thrown out as ruined and abandoned tracts."

Nor is it necessary that the subsoil be charged with salts for irrigation to produce alkali land ; the mere continual evaporation of ordinary river or spring water may cause such an accumulation of saline matter at the surface as is harmful to vegetation. This is well seen in Egypt, where perennial irrigation is practised with the Nile water, and the following quotation from Willcock's *Egyptian Irrigation* will explain the action that takes place :

" The introduction of perennial irrigation into any tract in Egypt means a total changes in crops, irrigation, and indeed everything which affects the oil. Owing to the absence of rain, the land is not washed as it is in other tropical countries, unless it is put under basin irrigation.

" An acre of land may receive as many as twenty waterings of about 9 cm. in depth each, i.e., a depth of water of 1·80 metre per annum, which is allowed to stand over the soil, sink about half a metre into the soil, and then be evaporated. Since the Nile water, especially in summer, has salts in excess, these salts accumulate at the surface, and if not eaten down by suitable crops, soon appear as a white efflorescence. While the spring level is low, capillary attraction cannot bring up to the surface the spring water, which generally contains a fair proportion of salts, but where the spring level is high the salt-carrying water comes to the surface, is there evaporated, and tends to further destroy the soil. In old times the greater part of the cultivation land was under basin irrigation, and was thoroughly washed for some fifty days per annum ; while the rest, consisting of the light sandy soils near the Nile banks, was protected by insignificant dykes, which dykes were burst every very high flood, and thus allowed to be swept over by the Nile and washed once every seven or eight years. All this is at an end now in the tracts under perennial cultivation, and other remedies have to be found."

The only remedy for the evils attending irrigation is the introduction of drainage channels at a lower level than the canals bearing the irrigation water ; in this way the percolation through the soil, which in humid climates naturally removes the salts not taken up by the crops, is effected artificially ; there is some apparent loss of water, but this is absolutely necessary to maintain the land free from injurious salts.

It was the neglect of drainage, when irrigation canals were introduced, that led to so widespread a deterioration of land in Egypt. To quote from Lord Milner's *England in Egypt* :

" But perhaps the worst feature of all was the neglect of drainage, which was steadily ruining large tracts of country. Even where drains existed, they were frequently used also as irrigation channels, than which it is impossible to conceive a worse sin against a sound principle of agriculture. In some cases these channels would be flowing brimful for purposes of irrigation, just when they should have been empty to receive the drainage water. Elsewhere the salt-impregnated drainage water was actually pumped back upon the land.

" It was the want of drainage which completed the ruin of the Birriya, that broad belt of land which occupies the northern and lowest portion of the Delta, adjoining the great lakes. There are upwards of 1,000,000 acres of this region, now swamp, or salt marsh, or otherwise uncultivable, which in ancient times were the garden of Egypt."

It has been the business of the English irrigation officers to restore and improve the drainage system, and to begin the reclamation of the salted areas by cutting drainage canals and passing enough of the abundant winter flood water through the soil to wash out the salts into these drains.

Hilgard in California has also indicated that it is impossible to wash the salts from the soil, even by leaving the water to stand upon the surface for some time, unless provision is made to remove the salted water by underdrainage. In the case of black alkali, however, the soil has become too impervious to allow water to percolate at all ; the first remedial measure is to incorporate considerable quantities of gypsum with the soil ; this will interact with the sodium carbonate, producing sodium sulphate and calcium carbonate, at the same time precipitating the humus in a flocculent form. If now underdrainage be brought into practice the soluble salts can be washed through, and a very fertile soil results, owing to the presence of the finely divided humus and calcium carbonate. Where underdrainage is hardly practicable because of the expense, irrigation water should be used in as limited amounts as possible, and every care should be taken to keep the surface tilled and under crop, so as to minimize evaporation from the bare ground. In humid countries like our own, damage due to the accumulation of salts is rare ; the author (A. D. H.) has, however, seen one case where the vegetation of a lawn was destroyed during a hot, dry spell of weather by continuously applying water in quantities which never washed down into the subsoil, but evaporated every day. An efflorescence practically identical with white alkali is sometimes seen on green-house borders, which are constantly watered, but never in sufficient quantities to cause percolation ; and gardeners again are familiar with the check of growth which sometimes occurs in the case of plants long in one pot and constantly watered with hard water. The remedy is to water from time to time so heavily as to cause abundant percolation and thus wash all the salts out.

Closely related to some of the phenomena presented by alkali soils are certain secondary effects upon the texture of the soil which are produced by the action of some of the salts used as artificial manures. A good friable texture in a heavy soil depends upon the clay particles being generally flocculated and gathered together into little aggregates, which give the soil a coarser grain until they are resolved into their ultimate particles by incautious working when the clay is in a wet state. It has already been stated that the clays rich in calcium are most easily flocculated and are least retentive of water, whereas the potassium and sodium clays are more gelatinous and sticky, dry less readily and are more easily dispersed. Again, whereas most soluble salts, notably those of calcium, are active flocculators, the hydroxides and carbonates of sodium and potassium have the reverse action and promote the dispersion of the colloid particles.

It has long been recognized that large or frequent dressings of nitrate of soda have an injurious action upon the tilth of the soil, causing it to remain very wet, and then to dry into hard, unkind clods. Since nitrate of soda is very hygroscopic, the wetness induced in the land was attributed to the absorption of moisture from the atmosphere by the nitrate of soda, but when it is considered what a very small proportion the water absorbed, by as much as 5 cwt. of nitrate of soda would bear to the hundred tons which is the approximate weight of an acre of soil an inch thick, it is obvious that the difference in water content so induced would not be sensible.

Clay soils, in fact, which have been treated with nitrate of soda, do not show any excess of water ; but they are very much dispersed, as may be ascertained by comparing the appearance after standing of a jar of distilled water rendered turbid by shaking up in it a gram of the soil, and a second jar in which the water has been shaken with a gram of the same soil in its normal condition. But nitrate of soda itself possesses flocculating powers even when concentrated, hence the observed deflocculation cannot be due to the direct action of the fertilizer upon the clay. The cause must be sought in the action of the nitrate of soda upon the clay colloids, whereby calcium is displaced and sodium enters the colloid with the formation of the hydrophile sodium clay. The analyses of the drainage water (p. 161) from the Rothamsted wheat plots show that dressings of nitrate of soda increase the leaching out of calcium, though analyses of the soil indicate that the nitrate of soda has protected the reserve of calcium carbonate in the soil, which has lost less than the soil from the unmanured plot. There must then have been a considerable replacement of calcium by sodium in the soil colloids. Moreover, it has been found that when plants feed upon a nutrient solution containing nitrate of soda, an excess of the nitric acid is withdrawn by the plant, and part of the soda is left in the medium combined with the carbon dioxide secreted by the plant. The existence of this soluble alkali after the growth of the plant can be verified by experiments with water cultures. Again, whenever nitrate of soda is destroyed by bacterial action with evolution of free nitrogen (denitrification) the soda base is left behind in the state of carbonate, and whenever the soil becomes for even a short period waterlogged and unaerated nitrate of soda will give rise to some alkali by this means. Soluble alkali derived from one or other of these sources can be extracted by water from the soil of the Rothamsted plots which have for many years been manured with nitrate of soda. Small as the amount may seem to be, it is, with the change from calcium to sodium clay, quite sufficient to account for the wetness and the defective tilth observed on heavy land after nitrate of soda has been used.

The bad repute of nitrate of soda as exhausting or scourging the land, is less due to any sensible diminution in the stock of plant food in the soil that follows its use, than to the deflocculation it sometimes induces, and the consequent deterioration of the texture of the soil. As a remedy, lime is not effective, since it is an alkali itself; instead, the nitrate of soda should be used in conjunction with acid-flocculating manures like superphosphate. A mixture of nitrate of soda and sulphate of ammonia may be used as the nitrogenous manure, because the two manures will act upon the soil in opposite ways, the nitrate of soda as an alkali and the sulphate of ammonia as an acid, though both add to the displacement of calcium in the clay colloids. Dressings of soot are also effective; not only does it assist the soil mechanically, but also the small percentage of sulphate of ammonia it contains possesses some power of flocculating the clay.

Other fertilizers that give rise to a more dispersible clay and sometimes to an alkaline reaction in the soil are sulphate of potash, common salt, and other soluble salts of sodium and potassium, the bases of which will replace calcium in the colloids. They may also interact with calcium carbonate in the soil, and give rise to a little soluble alkaline carbonate. The injurious effects of sulphate of potash upon the tilth of the heavy soil at Rothamsted is very evident on the mangold field, where the plots receiving this fertilizer every year become excessively sticky and clinging in wet weather, and dry with a hard caked surface. It has often been noticed that applications of potash salts and common salt have depressed instead of increasing the yield ; this may probably be set down to the deterioration of tilth that ensues when the soil is heavy. Some fertilizers, on the contrary, aid in the flocculation of clay soils, the most effective being superphosphate, which is acid and contains gypsum, an effective flocculating agent. The ammonium salts, which give rise to free acids, in consequence of the withdrawal of ammonia by the moulds, etc., living in the soil, act as very potent flocculators, and at Rothamsted, for example, give rise to an open and friable soil, as compared with the neighbouring plots receiving nitrate of soda. Lime, which is the chief flocculating agent employed in practice, is only effective when it has become dissolved as bicarbonate in the soil water.

Amendments of the Soil

Many soils, without being absolutely sterile, carry very poor crops until their physical character has been altered. In some cases this may mean changing the texture by admixture of some considerable quantity of one or other of the constituents of a normal soil that may happen to be originally wanting. It may mean the addition of organic matter or lime. Or it may mean the correction of a bad moisture-air status by drainage or irrigation. These amendments, which practically involve making a new soil, date from the time that enclosures first began to be made ; they were perhaps at their height during the early years of the nineteenth century, after the middle of which they rapidly diminished as it began to be less and less remunerative to " make " land, until at the present time the fall in the prices of produce and the rise in the cost of labour have put an end to all such operations. Among other causes of this neglect may perhaps be set down the increased use of artificial manures ; men began to take too exclusively a chemical view of the functions of the soil, and shirked expenditure which did not seem to add directly any food for the plant. However, it is possible that with war-time experience in aerodrome and other types of construction involving the moving of earth on a large scale by using mechanical power, the improvement of much poor land might again be profitably undertaken.

The operations which may be grouped under the head of "amendments of the soil," comprise—drainage, which has been dealt with elsewhere ; the marling and claying of light sands ; the improvement of clay soils by liming and chalking, or by paring and burning ; and lastly, the creation of new alluvial soils by warping.

Marling and Claying

Many light and blowing sands, almost too pure to permit of any vegetation, have in their immediate neighbourhood a bed of marl or clay which can be easily incorporated, practically creating a soil where there was none before. Among the New Red Sandstones of Cheshire and the Midland Counties beds of true marl occur and were at one time enormously worked, so that every farm and almost every field shows its old marl pit ; the sandy Lower Greensand soils in the Woburn district have been extensively marled from the adjoining Oxford clay, and many of the Norfolk soils have been made out of blowing sands, by bringing up the clay which immediately underlies them. The earlier volumes of the *Journal of the Royal Agricultural Society* contain numerous accounts, showing how much land was brought into cultivation by these means in the first half of the nineteenth century.

> "He that marls sand may buy the land,
> He that marls moss shall suffer no loss,
> But he that marls clay flings all away."

The usual practice in Norfolk was to open pits down to the marl or clay, dig and spread it at the rate of 50 to 150 loads to the acre on a clover ley or turnip fallow. In some cases trenches were opened all along the field, and the clay thrown out on either side. By the action of the weather, drying and wetting, followed by frost, the clay comes into a condition to be harrowed down, after which it can be ploughed into the ground.

The effect of marling or claying is more evident after a year or two than at once, because the fine particles become each year more thoroughly incorporated with the soil. The effects are to be seen in increased crops, the production of better leys and pastures, greater resistance to drought, and particularly an increased stiffness in the straw where manures are used to grow the crop.

Marl containing carbonate of lime is always far more valuable than clay ; pure clay is so little friable, and so sterile itself, that it effects an improvement only slowly ; marl not only ameliorates the texture but adds at once a supply of carbonate of lime, potash compounds, and in some cases phosphoric acid also. Clay and marl both have a tendency to sink, and eventually require renewing, but if well done will last for thirty to fifty years, because the accumulation of humus and fibrous root-remains, due to the increased crops, itself binds the soil together.

At the present day the need of marling or claying on a small scale is often seen in old gardens, particularly in old town gardens that are situated upon gravel soils, initially very short of the finer soil particles. The constant breaking of the surface by cultivation, and the use of large quantities of stable manure, which decays and leaves the soil open, result in a continual washing down of the finest particles, until the remaining soil loses all power of cohesion and of resisting drought, falling into a dusty powder immediately on drying. A coating of clay in the early autumn, or, better still, of good marl, is the only method of giving consistency to such a soil and soon remedies its worse defects, such as susceptibility to drought and rapid fluctuations of temperature, and tendency to produce soft vegetation, very liable to disease.

Paring and Burning

When the poorer clay soils were first taken into cultivation, a beginning was generally made by " paring " the surface with the breast plough, and " burning " the clods as soon as they were sufficiently dry. The clods were made up into heaps a yard or so in diameter, with the brushings of the hedges and all the rough surface vegetation, together with as much clay as was judged prudent. Each heap was then allowed to burn slowly and char the clay, without permitting the heat to rise sufficiently to vitrify the clay or dissipate such valuable material as the alkalis of the ash. The resulting ashes effected a great improvement in the soil : the clay was partially dehydrated, or at least coagulated, thus providing a certain amount of coarse material to ameliorate the texture ; in the charred clay also, some of the potash was rendered more available, whilst the plant residues provided mineral salts and alkalis to promote nitrification. The drawback to the process is the inevitable loss of nitrogen to the soil ; but any one who has noticed how freely crops grow on the patches of arable land where couch heaps have been burnt the season before will see that, for the time being, the fertility of the soil is increased by the process. Other advantages of burning lie in the destruction of weeds and insect life of all kinds, and although it has been almost wholly discontinued at the present day, the older writers on agriculture are unanimous as to its beneficial effects in bringing poor clay land into cultivation. The destruction of protozoa and the subsequent burst of activity on the part of the organisms producing plant food, is also doubtless a factor in the result.

A variation on the old process of " clod burning " consists in " border burning," in which clay is dug from one corner of the field and burnt by means of the couch and other weeds cleaned off the land, the hedge trimmings, etc. ; the burnt clay is then spread over the surface to improve the texture of the soil. Without doubt the latter process might still be profitably adopted where heavy clay land is under the plough ; if every year some clay were added to the fires made from the weeds and hedge trimmings, valuable material for lightening the soil would be obtained without wasting too much soil nitrogen.

Of course, the incorporation of any large-grained material will improve the texture of clay soils ; in some cases sand has been dug and spread with advantage ; road scrapings, town refuse, and even coal ashes help to lighten the soil, though in the case of gardens coal ashes should be avoided.

Liming and Chalking.

Of all the methods of improving the soil, other than actual manuring or cultivation, none is more important than the incorporation of lime or chalk. Large areas of lime-deficient soils occur in all parts of the country, but more commonly in the uplands of the north-west and west. On all such land liming produces very pronounced effects, both on the physical structure of the soil and on the character of the resulting vegetation.

It is on the clays and other strong soils that lime produces the greatest alteration in structure. The soil becomes much less retentive of water, percolation is increased so that the limed land is drier and warmer, admits of cultivation at an earlier date in the spring, and is far more friable when dry. In fact, the liming gives a coarser texture to the clay soil, and all the effects pertaining to the coarser texture, such as diminished capacity for retaining water and consequent greater warmth, less shrinkage and tendency to cake on drying, are all manifest after the application of lime. It does not, however, follow that the crop will mature more readily though the season is made earlier through liming ; in many cases in dry seasons crops upon clay ripen prematurely, because the drying up and shrinkage of the impervious clay cut the roots off from all access of moisture. The liming, by opening up the soil to the motion of water by surface tension, keeps the plant growing for a longer period ; at the same time, the increased amount of plant food rendered available also tends to prolong the duration of growth. On very light soils the addition of lime acts to a certain extent as a binding material, and increases the cohesion and water-retaining power of the soil, but it is not so effective in this respect as humus. Besides its physical effect upon the structure of stiff soils, lime has a very powerful chemical effect, liberating freely the reserves of plant food of all kinds in the soil and rendering them available to the plant ; so that on soils naturally deficient in carbonate of lime, manures of all kinds can find their proper value only if lime be also used from time to time. On soils that have been under intensive cultivation for a long time immense reserves of plant food have been accumulated, which require only the addition of lime to bring them into action. As an example may be quoted the result of applying lime to an old hop garden at Farnham, Surrey, where the soil consisted of an alluvial loam, very deficient in carbonate of lime, and heavily dressed with organic manures for many years previously. The plots chosen for comparison received a complete artificial manure with or without 1 ton of lime per acre ; the figures for the crops in the following table have been reduced to percentages to eliminate the great fluctuations due to season.

Year.	Artificial Manures.	
	With Lime.	Without Lime.
1895	100	70
1896	100	84
1897	100	80
1900	100	81
1901	100	90

Since lime sets in action the dormant residues already present in the soil, the forcing of crops by the aid of lime alone soon results in the exhaustion of the land. Hence the old saw—

> " Lime, and lime without manure,
> Will make both land and farmer poor."

The exact effect of lime in promoting fertility depends upon the plant food in question. We have already seen that all the decay processes which result in the oxidation of the humus are promoted by the presence of a base to combine with the organic acids produced by the decay, and, in particular, that the presence of an easily attacked base is necessary for nitrification. As a net result, the oxidation of the humus and the formation of nitrates is much increased by a dressing of lime, which, indeed, is the first indispensable step towards rendering available the rich organic residues accumulated in a sour soil. As regards the mineral constituents, lime has a very marked effect in bringing potash into a soluble state; the double hydrated silicates of potash and alumina, etc., which result from the partial breaking down of felspars and are the sources of the potash of our soils, are decomposed, lime being substituted for the potash going into solution. It is a case of mass action, where the addition of one soluble constituent to the soil will increase the amount that goes into solution of all the other constituents which are capable of being replaced by the base added; the extent of the action is therefore dependent upon the amount of lime used. The fact that more potash has been rendered available in limed soils is clearly seen in the character of the vegetation, e.g., in an increased proportion of clovers in the herbage of pasture or hay land. The action of lime as a liberator of potash is illustrated by the effect of a dressing of chalk applied in 1881 to part of the permanent grass plots at Rothamsted; by 1884 differences began to be manifest, the chalk caused a change in the herbage of those plots which had been receiving potash each year for twenty-five years previously, increasing the production as a whole, and particularly increasing the proportion of leguminous plants in the herbage. On the plots, however, which had been receiving no potash, and therefore contained no recently accumulated reserves of this material, the chalk had practically no effect, either in the weight or character of the crop.

To some extent lime seems able to act as a liberator of phosphoric acid in the soil. As pointed out by Thénard, lime is able to act upon the very insoluble phosphates of aluminium or iron which are present in many soils, and, by converting them into phosphate of lime, renders the phosphoric acid more available for the plant. Lime also increases the availability of soil phosphorus by promoting the biological oxidation of organic matter containing phosphorus compounds.

Besides its specific actions in thus rendering more soluble the soil constituents which nourish the plant, lime exerts a very beneficial action by maintaining the neutral reaction of the soil ; it neutralizes the acids produced by the decay and nitrification (see p. 174) of the organic matter in the soil. Again, as has been shown already, it is necessary as a base to satisfy the requirements of artificial manures like sulphate of ammonia, superphosphate, and kainit (see p. 160), or to prevent the soil being invaded by such organisms as the destructive fungus causing " finger-and-toe " see (p. 210). It must, however, be clearly realized that lime is wanted both as a base and as a compound of calcium. Calcium is necessary to the economy of the plant, and again, as has been said repeatedly, only the clays which are rich in replaceable calcium are readily amenable to cultivation. Only the carbonates of lime (chalk, limestone, etc.) or quicklime and slaked lime, which promptly become carbonate of lime when incorporated with the soil, are capable of acting as the required base. Other calcium compounds, as superphosphate of lime or sulphate of lime (gypsum), or phosphate of lime in bones, etc., are either acid or neutral, and do not supply the base required to effect the beneficial actions set out above ; they cannot replace lime or chalk—in fact, they do not contain any " lime " in the farmer's sense. Unfortunately, it has been too often supposed that the use of artificial manures, such as superphosphate of lime, removed the necessity of a periodical liming of the soil, and some of the neglect into which this all-important operation has fallen may be set down to the unfortunate confusion hanging round the word lime. However, as will have been gathered from a consideration of the effects of sulphate of ammonia in depleting the Woburn soil of carbonate of lime, the use of artificial manures generally demands an increased rather than a lessened attention to the periodical liming of the land.

In many parts of the country, the traditional lime dressing has been quicklime in lump form. This was first set out in small heaps of about half a hundredweight and allowed to slake, and then spread by a shovel. With the heavy dressings formerly used, up to 5 or more tons per acre, skilful workers could make a very even spread. Where less than 2 tons per acre are used, it is very difficult to secure uniform spreading, and in parts of the country where liming has not been maintained as a regular practice, very uneven spreading may be seen. In the south and east of the country, lime was often applied in the form of soft chalk. Very large dressings were given. For instance, at Rothamsted, more than 100 tons per acre must have been applied before the close of the eighteenth century by sinking pits through the " clay with flints " down into the underlying chalk and spreading the dug-out material over the surface.

In many districts, although liming had almost died out before the present war, substantial reserves of lime remained in the soil from past dressings. It is certain that in the heyday of liming, lime must have been applied far in excess of the actual needs of the soil. The farmers of the present generation thus owe a great debt to the generosity of their forerunners.

The neglect of liming during the latter part of the last century and up to the outbreak of the present war has had lamentable results for our national agriculture. A recent estimate of the area of lime-deficient soil in Great Britain puts the figure at over 16 million acres. The position has somewhat improved since 1937 as a result of the introduction of the Lime Subsidy, but much remains to be done before the soils of the country reach a satisfactory lime-status.

It is no longer economical to give the heavy dressings that were used in past generations. It is better to give smaller dressings at regular intervals. In order to avoid wasteful use, it is very necessary that all dressings should be given according to the needs indicated by soil analysis. In this way the use of lime on land already well supplied with lime is avoided. Apart from its wastefulness, over-liming may result in plant nutrient troubles such as boron deficiency in swedes and beet, and manganese deficiency in oats and peas.

The farmer has a wide choice of lime dressings. In practice this choice is generally between some form of quicklime on the one hand and on the other some form of calcium carbonate such as ground limestone, ground chalk, or waste limestone dust. There are also available in some districts waste calcium carbonate from sugar-beet factories and other industrial plants.

Generally speaking, it may be assumed that with equal efficiency of distribution, lime is as effective in the form of carbonate as in the form of quicklime. The advantage of quicklime is that it is the most concentrated form of lime. The cheapest form is lump lime, but against its cheapness may be set the difficulty of securing an even distribution and the cost of slaking and hand spreading. Ground lime may be spread by means of a drill, but is very unpleasant to handle and dangerous to store on account of the heat developed in slaking. Ground limestone or ground chalk is as effective, lime for lime, as quicklime, and has the advantage that it is more easily handled and can be stored safely without risk of fire or deterioration.

Warping

The operation of "warping," or "colmetage," is only possible in the vicinity of tidal estuaries, where lands exist below the level of high-water, and is in this country practically confined to the estuaries of the Humber and Ouse. Warping is carried out by the construction of a wide drain protected by sluices from the tidal river to the low land, which is first divided by embankments into compartments of various sizes, up to 150 acres. When the embankments have become consolidated, the flood tide, heavily charged with suspended matter, which is really fine earth brought down by the river, is admitted into the compartment, where it deposits most of its silt and is allowed to run off when the level of the water in the river has fallen during the ebb. The operation is repeated until a layer of silt has formed 1 to 3 feet thick over the land, which is then dried and brought under crop. As the chief deposit is always near the mouth of the drain, where the velocity of the silt-bearing current is first checked, the position of the inlet must be shifted about to secure a uniform deposit all over the land and to distribute the valuable fine silt which settles farthest from the inlet. In some cases the sluice gates are automatic, and water is admitted and drawn off at every tide, but in others only every other tide is admitted, thus giving time for the deposit of the finer particles, and greatly improving the character of the resulting land. As a rule, only the spring tides are utilized, because the suspended matter is then at its maximum, and the process is confined to the summer months, to avoid danger from flooding when there is much land water about. In exceptional cases land may be warped 2 or 3 feet deep in one year—from January to June—in other cases, where the water is less charged with sediment, or the land is at a higher level, an efficient warping, which should not be less than 18 inches deep, requires three or four years. When finished, the land is allowed to dry and consolidate, drainage grips are then thrown out, and a light crop of oats, in which are sown clover and rye-grass, is taken ; after the seeds have been down two years the land is generally ready to carry wheat. Warp soils are, as a rule, fertile, and noted for growing seed corn of high quality ; they are to all intents and purposes artificial alluvial soils, composed entirely of the finer sands and silts without much clay material, and are comparatively rich in organic débris and other plant food, except perhaps potash. The fertilizing of the Egyptian land by the red Nile flood water, the formation and improvement of river meadows by winter flooding, are both analogous to the process of "warping."

Reclamation of Peat and Heath Land

One of the earliest methods of bringing peat land in the Fens and similar districts into cultivation, was to dry the land by means of open drains and break up the surface with the breast plough ; the clods were then gathered together, and burnt when dry, afterwards the ashes were spread and a crop of rape taken. The fire was never allowed to burn too fiercely, the object being to obtain charred residues rather than white ashes. The effect of burning the peat was to provide a certain amount of ash rich in saline matters and particularly in alkaline carbonates, thus correcting the two great faults of the remaining peat, its deficiency in mineral matters, and its sour reaction. At the same time the weeds and other coarse vegetation occupying the surface were destroyed, and a clean seed-bed prepared for the crop. However, the process of burning is a very wasteful one, involving the loss of the combined nitrogen contained in the accumulated organic matter, and after a few repetitions the land was found to be seriously depleted of its reserves of humus. Burning became replaced in the Fens by a marling process, especially where the peat was of a sandy nature ; trenches were opened to the bed of marl or clay always found beneath the peat, and the clay thrown out and spread at the rate of 100 loads or so per acre, the burning process being reserved for the first reclamation, when a mass of surface vegetation had to be got rid of. In other districts, where marl is less available, peat has to be brought into cultivation by draining the land with open cuts, allowing some considerable time to elapse during which the peat dries, shrinks, and consolidates, and then correcting the acidity with lime.

It is in Germany and Holland that the reclamation of peaty areas has been most systematically pursued. The process must begin with a thorough drainage of the area, either by cutting off the sources of the incoming water or by deepening the outlet, so as to lower the permanent water level to some distance below the surface of the land. According to the conditions, the area may require a system of drainage cuts and open ditches to get away the water, which the peat parts with slowly because of its colloid nature. The consolidated peat may be removed if there is a market at hand for peat fuel, but the loose, less rotted material near the surface is thrown back to form the soil. Where the land is to be used for arable cultivation it is very desirable to spread a layer of whatever soil is available below the peat, even if it is pure sand. The rough vegetation on the surface is carefully burnt off and the fundamental manuring upon which the cropping depends is then applied. This consists of from 2 to 4 tons per acre of ground chalk or marl, about 5 cwt. of basic slag, and 6 to 8 cwt. of kainit or other potash salts, all of which are well worked into the surface soil with cutivators and harrows of the disc type before cropping begins. The chalking will have to be repeated in a few years, and the basic slag and potash salts need to be regularly applied, though not in the initial quantities. On a newly reclaimed bog the horses require special shoes or boots with broad flat soles, and the wheeled implements are fitted with wide flat bands in order to enable them to traverse the spongy surface without sinking in. Good crops can be grown cheaply after the initial reclamation, for the land contains an immense reserve of nitrogen. Rye and oats among cereals, potatoes, mangolds, cabbage and kale form the best crops ; the quality, and especially the stiffness of the straw of the cereals, are very dependent upon the incorporation of some mineral soil in the cultivated layer.

Permanent pastures may be formed by burning over the surface, incorporating the chalk and manures with the burnt ashes by a series of shallow cultivations and sowing the seed mixture, in which alsike clover, trefoil, timothy, and cock's-foot and rye grass should predominate, in the spring without any cover crop. In Germany, reclamations of the low-moors, the wet peaty alluvial deposits near the river-mouths are regarded as the most profitable undertakings of this nature, the financial results being in the main dependent upon the cost of the initial drainage.

High-moor or moss peats are less promising for reclamation than lowland or fen peats. Their status in lime and the other plant nutrients is exceedingly low, so that, apart from drainage and the initial operations necessary for producing a seed-bed, lime, phosphate, potash, and even nitrogen must be given. Indeed, even when these have been given, minor element deficiencies may still limit production. In Holland, for example, a so-called reclamation disease of peat soils was found to consist in a deficiency of copper. A further disadvantage of the high-moor peats is that they often occur in bleak and unfavourable climatic regions.

In spite of all these disadvantages, some success has been obtained in Scotland in the reclamation of moor peats. The first operations consist in drainage, in which full use is made of modern excavating machinery. After drainage, lime at the rate of about 2 tons per acre is given. It is usual to apply half the dressing before ploughing, disking it well in after distribution. The remainder is applied after ploughing and again worked in with disk harrows. Heavy dressings of artificial fertilizers must be given until a reserve has been built up in the soil. Annual dressings of 130–150 lb. P_2O_5 as slag or mineral phosphate and 150–170 lb. K_2O as potash salts may be given. These may be decreased in later years. In addition, about 40 to 50 lb. of nitrogen must be given, generally as nitro-chalk or nitrate of soda, although sulphate of ammonia may be given when the soil has been thoroughly limed. The nitrogenous fertilizer may be diminished or omitted for leguminous crops.

Much of the difficulty in peat reclamation consists in breaking down the rough matted surface to form a seed-bed. Where possible, this is pared off, dried, and burnt. Special types of implements are used for cultivation, and a satisfactory tilth may not be obtained until the second or third year. Generally speaking, the objective of this type of reclamation is the establishment of good grassland for hay or grazing, and the crops taken after reclamation should be regarded as preparatory to seeding out.

The treatment of the great area of heaths which covers the coarse sandy glacial deposits of Northern Europe follows much the same lines as that used in the reclamation of peats, and might be applied to considerable areas in Great Britain, as, for example, to the " brek " land of Norfolk and Suffolk, the Dorset and Cornish heaths, etc. In all these areas, farms are to be found reclaimed at some time or other from the heath, which alongside is still waste. The farms are often poor because the soil has only been made by a long process of cultivation and cropping, without attention to the fundamental amelioration of the soil by a supply of lime, phosphoric acid, and potash. Success in reclamation is entirely dependent upon the courage with which this initial expenditure necessary to " make " the land is faced. It is difficult to say at the present time whether the demand for land will repay the high costs now to be incurred.

The work of reclamation must begin in many cases with drainage ; shrubs and trees have to be removed ; banks roughly levelled and hollow places filled in ; then the heather, if present, is burnt over and a steam cultivator or deep tractor should be set to work. It is sometimes necessary to break up an iron pan existing a few inches below the surface. The ameliorating materials are then sown, 2 to 4 tons of chalk, 6 to 8 cwt. of basic slag, and 5 to 6 cwt. of potash salts per acre ; subsequent shallow cultivations work in the manures and remove the moss, bracken roots, and other rough vegetable débris. For arable land the best preparation is to sow a crop of blue lupins, to be turned in and supply a stock of nitrogen and humus for succeeding crops. Vetches also may be used and folded off with sheep. For the subsequent cropping rye and oats are the best cereals ; potatoes, carrots, and peas give good crops, and the land may be sown down to lucerne succcessfully. Continuous manuring is indispensable, nitrate of soda is better than sulphate of ammonia, and potash salts cannot be omitted. Early sowing is also a very necessary feature in the management. A very successful experiment of this type was made on some 200 acres of the " brek " land at Methwold in Norfolk, land which was covered with bracken and had never previously been cultivated. In the second year after breaking up, the land was yielding 27½ bushels per acre of wheat and 28 of oats.

During recent years large areas of inferior grassland in our upland regions have been ploughed up and laid down to improved pastures. Much of this land consists of " intakes " or " inby " land in the marginal belt between lowlands and uplands. Owing to the general depression of agriculture and particularly of sheep farming, these enclosed lands, which formerly carried valuable grazing or hay herbage, became neglected and underwent deterioration. In some cases they had become rush-infested through bad drainage ; in other cases they had become occupied by an inferior herbage of *Molinia*, *Nardus*, fescues, and even heather. Even more serious was the invasion of vast areas of the drier lands by bracken.

A variety of methods of reclamation has been used with success. In some cases the land has been directly reseeded, in other cases pioneer crops such as rape, hardy green turnips, and even potatoes have been grown before seeding down.

The principal operations in reclamation are drainage where necessary, liming, dressing with phosphate and, in some cases, with nitrogenous fertilizers, and, most important of all, the preparation of a seed-bed. Here, it is necessary to ensure that the rough matted vegetation is well turned under and that there shall be a sufficiency of lime to ensure its rotting down. On account of the extremely low nutrient status of these soils, it is necessary to follow up the original reclamations with continued good management, including further dressings of slag or lime.

CHAPTER X

CLASSIFICATION AND MAPPING OF SOILS

Practical Classification by Texture—Geological-Petrographical Classification—Climatic Classification—Classification by Vegetation—Systems of Classification based on the Soil Profile—Soils with Free Drainage : Leached Soils ; Incompletely Leached Soils—Podsols—Brown Earths—Tropical Analogues of Brown Earths—Prairie Soils—Tshernosems—Chestnut Earths, etc.—Tropical Analogues of the Tshernosem Succession—Soils with Impeded Leaching—Gley Soils—Peat Soils—Saline, Alkaline, and Soloti Soils—Soil Surveys, Productivity-rating and Land Classification.

IN the study of any natural material, the need for a system of classification arises at an early stage—not at the earliest stage, because a system of nomenclature comes first. In the case of soils, nomenclature has remained at a primitive stage until comparatively recent times. Practical men soon learned to distinguish between light and heavy soils, and most soil names refer to texture, e.g. clays, loams, and sands. Thus, the earliest attempts at classification were based on texture. These systems were essentially elaborations of the practical man's categories, but an attempt was made to give them more precision by translating them into terms of mechanical composition. For example, in the United States the following main textural groups are recognized :

	Silt + Clay per cent.	*Clay per cent.*
Sands	Less than 15	Less than 20
Loamy sands	15–20	,, ,,
Sandy loams	20–50	,, ,,
Loams and silt-loams	over 50	,, ,,
Clay-loams		20–30
Clays		over 30

Each of these textural classes is further subdivided, for example, the sandy loams are subdivided into coarse sandy loams, sandy loams, fine sandy loams, and very fine sandy loams.

In Great Britain, no numerical standards have as yet been laid down for textures, but the following grades have been recognized for soil survey purposes. They are based on a field assessment of texture by handling.

Sa	Coarse sand
Sb	Fine sand
La	Light loam
Lm	Medium loam
Lb	Heavy loam
C	Clay
Z	Silt

Apart from difficulties in securing agreed standards, the main obstacle to a closely defined system of grades based on mechanical analysis is that the texture of soil is affected by other factors than mechanical composition. The percentage of organic matter is of significance, because a high organic matter content will mitigate the heaviness of a clay soil and give "body" to a light sandy soil. There are also differences depending on the actual character of the clay. Siliceous clays have the characteristic clay properties more strongly marked than sesquioxidic clays. Soils may be found in the tropics with 50 per cent. or more of clay by mechanical analysis, which nevertheless behave as friable loams on account of the sesquioxidic character of their clay.

When the properties involved in texture as a physical property are more clearly understood, it may be possible to devise a numerical system of textural grades based on mechanical composition, organic matter content, and clay composition. In the meantime, mechanical analysis gives a useful approximate check on the field estimate of texture among soils of the same general constitution.

In an earlier chapter, the distinction between soil as material and soil as an individual was stressed. Texture is a property of soil material and as such can have only a limited application to the problem of soil classification in its broadest aspect. Even if a perfect system of texture classification had been devised, it would by no means follow that soils grouped together in one texture class would resemble each other in properties other than texture. The importance of texture must not, of course, be minimized. It is one of the most important characteristics of the soil and is of the highest significance for its physical behaviour. Whilst of slight value in a major classification of soils, it may be usefully employed to distinguish related soils that are similar in other respects.

The problem is, then, to classify soil individuals rather than to classify soil material. As in the study of other natural objects, the study and recognition of varieties of soils proceeds *pari passu* with efforts at arriving at a system of soil classification. The aim is to arrange the known varieties of soil in such a sytem as shall best indicate their genetic relationships. Two serious difficulties always exist in the way of this attempt. In the first place, varieties of soil are not as clearly defined as the genera and species of plants and animals. Secondly, in a long settled country such as our own, most of the soils studied have been considerably modified by the effects of human action. A scientific system of classification should be based on the characters of the soil in its natural state. It is therefore always necessary to make some assumptions as to the nature and extent of the modifications in the profile consequent on human interference. This may to some extent explain why countries such as the United States and Russia with their vast areas of soil under natural vegetation or comparatively recently won from this state, have been able to contribute far more to the solution of the problem of soil classification than our own country.

Geological-Petrographical Classification

Anyone familiar with the soils of England and Wales cannot fail to be struck by the great influence exerted by geology on the character of the soil. Travelling across the country from north-west to south-east, i.e. across the strike of the great geological formations, the landscape and soil change with the geology, and it is possible to tell, from the general land forms and the appearance of upturned soil, the formation that is being crossed. Of course, some formations are more easily recognized than others. The Chalk, Carboniferous Limestone, Old Red Sandstone, and Oolitic Limestone are easily recognized by their soils. It is not so easy to distinguish the clay formations from each other. The Gault, Oxford Clay, and Kimmeridge Clay areas, for example, look very similar viewed superficially. Areas covered by glacial drift are particularly difficult, but boulder clay country is generally easy to recognize by its relief, even if the actual character of the drift is not evident.

In view of this close connexion between geology and soil in Western Europe, it is not surprising that attempts have been made to classify soils on a geological, or more strictly, a petrographical basis. For example, soils have been classified according to their derivation from :

(1) Crystalline rocks.
(2) Shaly and schistose rocks.
(3) Limestones.
(4) Conglomerates, grits, and sandstones.

Each of these main classes may be further subdivided. For example, soils from crystalline rocks may be subdivided into those from acid, intermediate, and basic rocks, and these subgroups again subdivided into volcanic, hypabyssal, and plutonic.

It is obvious that such a classification depends for its validity on the strict correspondence between rock and resultant soil. Where this exists, the geological-petrographical system may prove useful. It was used in most of the earlier soil surveys in England. For example, Hall and Russell in their soil survey of Kent, Surrey, and Sussex, distinguished Chalk soils, Wealden soils, Gault soils, and so on. Within the area studied by them, the classification was fairly satisfactory.

The geological-petrographical system, however, has serious limitations. The strictly geological system, indeed, breaks down at once when there is a change in the character of the rock as one formation is followed across the country. Thus, the Middle Lias of Oxfordshire is quite different in lithological character from the Middle Lias of Dorset. To speak of a Middle Lias soil would, therefore, be meaningless. But even when the same kind of parent rock is considered, the resultant soils will differ according to the climatic and topographical factors that enter into soil formation. Ordovician shales under lowland conditions with free drainage, under lowland conditions with impeded drainage, and under upland conditions with free drainage develop quite different soils. When the same rock is studied under widely differing climates, the differences between the resultant soils may be fundamental. A basic igneous rock in Britain would give rise to a soil entirely different from that produced from the same kind of rock in a humid tropical climate or in a temperate arid climate.

Another complication in the application of the geological-petrographical system is introduced by the drifts. Glacial drift, for example, may be classified into boulder clays and fluvio-glacial sands and gravels. The actual character of the drift, however, is governed largely by the material from which it is derived, and this is not always plainly evident. There is, therefore, a wide range in the character of soil derived from drifts, and even if the petrographical basis is to be applied, information must be obtained as to the petrography of the drifts.

The geological-petrographical system is in fact no more than a classification of parent materials, and cannot be a classification of soils. Nevertheless, within a limited area, it may prove useful in distinguishing between soils of the same general class. It may also be convenient to group together soils derived from the same parent material in order to study the effect on soil formation of the different factors of soil formation, such as climate, ground-water conditions, topography, etc.

Climatic Classification of Soils

Whilst students of the soil in Western Europe were seeking to classify soils according to their geological origin, an entirely different approach to the problem was being made in Russia. This was natural, for the Russian Empire stretched across vast distances from the northern forests across the steppes to the desert. Therefore, whilst the Western European investigator, surveying a comparatively small area of relatively uniform climate, saw the causes of the differences between soils in the geology, the Russian soil investigator, conscious of a wider range of soil conditions, saw climate as the dominant factor in soil formation, and thus sought to classify his soils according to the climatic conditions under which they were formed.

The founder of the great Russian school of soil scientists was Dokuchaiev, whose first works on the classification of soils appeared in the 70's of the last century. It is to Dokuchaiev, before all, that we owe the conception of the soil as a natural body. He was the first to see clearly the general picture of soil formation as consisting of the operation of a number of factors on a geological parent material.

A convenient and simple classification of soils according to climate was put forward by Vilensky. He recognized five temperature classes, namely: polar, cold, temperate, subtropical, and tropical; and five humidity classes, namely: humid, semi-humid, medium, semi-arid, and arid. By combining these, twenty-five sets of climatic conditions are obtained, e.g., polar-arid, cold semi-arid, temperate-humid, tropical-arid, and so on. Certain of the well-known classes of soils are placed into these climatic groups. In some cases, however, it would appear that hypothetical classes of soil have been invented to fit the system.

Classification of Soils by Vegetation

Although no comprehensive system of soil classification based on natural vegetation has been proposed, soils are often referred to as characteristic of some of the more important plant associations. Thus, in the literature, reference is made to coniferous forest soils, heath soils, rain-forest soils, prairie soils, and steppe soils. Whilst such terms call attention to the correlation between soil and vegetation, they cannot provide the basis for a soil classification.

Systems of Classification based on the Soil Profile

Classifications based on parent geology, vegetation, or climate are not, strictly speaking, classifications of soils, but classifications of geological materials, vegetation, and climate, respectively, adapted to the purpose of studying soil. This fact was clearly appreciated by such workers as Treitz, Frosterus, Glinka, and, above all, Marbut in the earlier years of the present century. Marbut, formerly Chief of the United States Soil Survey, through his writings and, still more, by his extraordinary personal influence, did more than anyone else to inculcate the study of soils as soils, and to teach the student of the soil to look to the actual characters of the soil profile for the basis of his classification.

Many schemes have been proposed for a world classification of soils. A final classification still remains to be made, because there are large tracts of the earth whose soils have not yet been examined by modern methods. The following scheme may be put forward tentatively to cover most of the kinds of soil already known.

A. *Soils with free drainage*

- 1. Leached soils (humid climates) :
  - (*a*) Presence of raw humus
    - Podsols.
  - (*b*) Absence of raw humus
    - Grey-brown podsolic soils.
    - Brown earths.
    - Degraded tshernosems.
    - Prairie soils.
- 2. Incompletely leached or pedocalic soils (semi-arid and arid climates) :
  - (*a*) In temperate climates
    - Tshernosems.
    - Chestnut earths.
    - Brown semi-desert soils.
    - Grey semi-desert soils.
    - Desert soils.
  - (*b*) In tropical and sub-tropical climates
    - Tropical tshernosems, etc.

B. *Soils with imperfect or impeded drainage*

- 1. Absence of sodium salts :
  - (*a*) Absence of peat
    - Gley soils.
    - Vlei soils.
  - (*b*) Presence of peat
    - Peat soils.
- 2. Presence of sodium salts
  - Saline soils.
  - Alkaline soils.
  - Soloti soils.

Before describing the principal soil groups, it is necessary to emphasize again that soils do not fall into defined genera and species like animals and plants. Certain broad groupings can be made, but within these groups there are wide variations. When an attempt is made to break down these groups into ultimate categories, it is found that a large proportion of the soils to be classified have to be regarded as transition types. The further subdivision of the great soil groups will be further discussed at a later point.

Soils with Free Drainage

Soils with free drainage are found in situations and with structures permitting the free percolation of soil moisture down the profile, generally good aeration, and the consequent prevalence of aerobic conditions. They may be subdivided into two major groups, roughly corresponding with Hilgard's earlier division into humid and arid soils.

Leached Soils.—In the first of these major groups, occurring under humid climates, i.e. where rainfall predominates over evaporation, the profile is completely leached, which means that soluble salts including calcium carbonate, are eventually washed down to the water-table and thence into the local drainage system. The natural vegetation is generally forest, scrub, or heath, but one class of these soils, namely the prairie soils, is found under tall grass vegetation. The group may be subdivided according to the presence or absence of raw humus in the upper horizon of the profile.

Incompletely Leached Soils—In the second great group of the freely drained soils, occurring under semi-arid and arid climates, evaporation predominates over rainfall. The profile is incompletely leached, for the rainfall is insufficient to provide an excess of moisture to reach the water-table. There is thus between the soil profile and the regional water-table a zone that is ordinarily unaffected by the rainfall falling on the soil and remains permanently dry. The rainfall moistens the soil to a limited depth and this is followed by drying out. Soluble products of weathering, principally calcium carbonate and calcium sulphate thus remain in the soil profile and tend to accumulate at the depth to which moistening extends. The presence of an horizon of calcium carbonate accumulation is thus a characteristic mark of these soils. The natural vegetation varies with increasing aridity from prairie or steppe to desert. Corresponding with these changes in climate and vegetation, changes occur in the soil profile. Organic matter decreases in amount and the horizon of calcium carbonate accumulation becomes more pronounced and approaches the surface more closely. Soils of this group are termed *pedocals.*

Podsols

These soils are developed under conditions of free drainage in humid climates. It was formerly thought that they were confined to cool and temperate regions, but true podsols have now been found in the tropics, although they are not common. The natural vegetation is coniferous forest or heath, and the condition dominating the development of the profile is extreme acidity and, therefore, low base-status. Under these conditions, the leaf-fall and other residues accumulate as a surface layer of raw humus. Under the influence of the extremely acid humic leaching that takes place, the colloidal complex undergoes a decomposition and sesquioxides, together with humus, are removed from the surface horizons and deposited in lower horizons. The profile thus consists essentially of the following horizons :

A_0.[1] Raw humus horizon.
A_1. Dark-coloured or black mineral soil rich in humus.
A_2. Bleached horizon, low in sesquioxides and humus.
B_1. Dark-coloured horizon enriched in humus.
B_2, B_3, etc. Rusty brown, orange, or yellow horizons, enriched in sesquioxides.
C. Parent material.

Considering the horizons in more detail, the A_0-horizon may be subdivided into an F or litter layer and an H or humus layer. The humus layer is generally not more than a few centimetres thick. It is dark brown or nearly black in colour and contains practically no mineral matter. Various structures are found, such as granular, fibrous, or amorphous. The base-status is exceedingly low and rain falling on the soil dissolves acid humic matter from this horizon.

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[1] The lettering of the horizons follows the generally accepted convention.

The A_1-horizon is not always clearly seen. It is a thin black horizon in which humus is intimately mixed with the mineral soil. It may be regarded as a transition to the next horizon.

The A_2-horizon is characterized by its bleached appearance, which extends to stones and pebbles included in the horizon. The structure is loose and dusty when dry and there is often a tendency to lamination, i.e. a plate-like structure.

The B_1-horizon is not always recognizably present. Generally it appears as a thin coffee-brown or almost black layer. The boundary between the A_2 and this horizon is often very irregular, and deep tongues of A_2 material may extend below the general level of the boundary. The B_1-horizon is more compact than the A_2-horizon and is often indurated. In coarse-textured soils, it may sometimes form an almost rock-like pan extending into the upper part of the horizon below. If the material of this horizon is boiled with hydrogen peroxide to destroy humus, it generally shows a bleached appearance like the horizon above, indicating the absence of sesquioxide deposition. This is not, however, invariably the case. Where the horizon is very thin, sesquioxides appear to be deposited together with the humus.

Below the humic B_1-horizon just described, we find the horizon or horizons of sesquioxide deposition. These may form two or three fairly distinct horizons or one horizon with a gradual change to parent material. Colours are generally rusty-brown, orange-brown, or yellowish-brown depending on the mode of deposition of the ferric oxide and its degree of hydration. Hydrated alumina is also present, although generally in smaller amount. The B-horizons are fairly compact, particularly in the upper sub-horizons. In addition to accumulation of sesquioxides, there may also be some accumulation of phosphate, leached out from the A-horizons.

Apart from chemical eluviation, there is also a certain eluviation of clay, resulting in a light textured A-, and a heavier textured B-horizon.

In the frontispiece is seen a photograph[1] of a podsol profile developed under heath and scrub at Goldstone, near Newport, Salop. The parent material is Bunter Pebble Bed.

Agriculturally, podsols are naturally poor soils. They have a very low base-status and the surface soil has a poor structure. If they are brought into cultivation, liberal manuring with lime and phosphate is necessary. It is often desirable to incorporate some of the ferruginous B-horizon with the bleached A-horizon in order to increase its content of colloidal matter. If a pan is present, this must be broken by subsoiling or other means.

There are many variants of the podsol profile. A common variant is a profile in which the humic B_1-horizon is missing or not recognizable. The bleached A_2-horizon is then succeeded directly by the ferruginous B_2-horizon. This is a less extreme type of podsol and often occurs on shaly parent material in Wales and Scotland. It may be presumed that such materials have reserves of base that oppose podsolization.

Where land formerly in coniferous forest or heath has been changed by management or grazing to a grass vegetation, one often finds a masked podsol, in which the bleached character of the A_2-horizon is masked by the presence of organic matter from grass roots. The structure is also modified to a more crumbly or granular type. In such profiles the dark-coloured surface horizon merges directly into the ferruginous B-horizon.

In some of the hill districts of Scotland and Wales soils are found in which the surface horizon is of a sesquioxidic character reminiscent of a podsolic B-horizon. These may be considered as truncated profiles in which the bleached layer has been removed, either catastrophically by erosion following cultivation, or else by the continued operation of normal erosion. These soils may occasionally undergo a secondary podsolization.

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[1] Specially taken for this edition by Mr. W. Morley Davies, whose help is here gratefully acknowledged.

Lastly, the development of a strong B-horizon with induration may restrict drainage and the profile may become of an impeded drainage type. The residues of vegetation now tend to accumulate as peat and finally a peat soil develops. In the Welsh mountains, deep peat is often found overlying mineral soil with podsolic horizons, which were formed in an earlier stage of development.

The mechanism of the podsolization process is not completely understood. The high acidity and the presence of humic materials in the leachings readily account for the removal of sesquioxides from the surface horizons. The mode of deposition of humus and sesquioxides in the B-horizons is not so clearly understood. According to one theory, they are precipitated from descending solutions as a consequence of the higher base-status of the lower horizons. Another theory is that they are deposited from solution during dry periods, when capillary movement is to a limited extent in an upward direction in the lower layers of the profile.

Brown Earths

These soils are less intensively leached than the podsols and have a higher base-status. They are, however, definitely base-unsaturated and their reaction is on the acid side of neutrality. Calcium carbonate is not naturally present, but as most of these soils in Britain are in agricultural use, it may be present as a survival from the lime dressings given in the past. The natural vegetation is deciduous forest or scrub. Because of the higher base-status, there is no layer of raw humus. The leaf-fall and residues of ground vegetation are decomposed to form the so-called "mild humus" and distribution throughout the profile takes place through the work of earthworms, which are relatively abundant. There is no leaching out of sesquioxides and therefore no development of a bleached surface horizon.) At the same time, the sub-acid reaction and the low base-status result in some liberation of hydrated sesquioxides, and brownish colours develop, somewhat masked by the presence of organic matter in the surface soil. The structure is generally a good crumb or soft granular type, sometimes passing to a nut structure in the subsoil. In very mature profiles, there may be some mechanical eluviation, leading to the development of a lighter-textured A-horizon and a heavier B-horizon. In extreme cases, this may result in restricted percolation, so that the soil develops the characters of an impeded drainage profile.

Since there is no eluviation of sesquioxides, the clay complex remains approximately constant in composition down the profile. Any tendency to podsolization is reflected in the composition of the clay fractions of the A- and B-horizons, before being recognizable by field examination.

Most well-drained English soils may be assigned to the brown earth group. Centuries of agricultural use, however, have considerably modified the character of the profile. In arable soils, all horizons down to the depth of cultivation have been mixed together and show no differentiation. There may also be changes in structure. Maintenance under grass also modifies the original character, above all by raising the organic matter status.

All transitions from podsols to brown earths can be observed, but there is a group that might be given separate recognition, namely the *grey-brown podsolic soils*. These are soils of lower base-status than the brown earths, showing some podsolization owing to slight translocation of sesquioxides. They grade into the podsols on the one hand and into the brown earths on the other. They are definitely superior in agricultural value to the podsols, but rather inferior to the brown earths, escept that, occurring under generally humid climates, they may be turned into good grassland by suitable manuring and management. Most of the freely-drained soils of Wales and Scotland might be assigned to this group.

Parent material as well as climate determines whether podsols, grey-brown podsolic soils, or brown earths develop in a given situation. Where the parent material is rich in basic material, podsolization is hindered and a grey-brown podsolic soil or a brown earth develops, even under a cool wet climate. For example, in Iceland, where the climate might be expected to favour podsolization, basic igneous rocks give rise to brown earths. On the other hand, even in a fairly warm and dry climate where brown earths might be expected, parent materials poor in bases form podsols, as, for example, the well developed podsols on the poor quartzose sands of the Bagshot Beds in Surrey.

Vegetation also plays a part although it is itself conditioned by soil and climate. An artificially induced change of vegetation may result in a change of soil. For example, where scrub oak forest over brown earths or grey-brown podsolic soils has been cut down and replaced by conifers, podsolic soils develop, as in the Delamere Forest of Cheshire.

Tropical Analogues of the Brown Earths

Red soils occur very widely in the tropics, and show certain affinities with the brown earths of temperate climates. There are, of course, important differences between the processes of soil formation in tropical and temperate climates, but there is an equally important difference in the parent material and some of the more obvious differences between tropical and temperate soils may be due to the parent material rather than to the character of the soil-forming processes. Primary weathering in the tropics is more intense, corresponding with the higher temperatures, and has operated for longer periods than in Britain, where weathering dates back only to the close of the last Glacial Period. The weathered product from crystalline rocks in the tropics has undergone more complete desilicification and is consequently more sesquioxidic than the corresponding material in temperate climates. The predominantly red colours may be attributed to free ferric oxide with a comparatively low degree of hydration. The characters of tropical soils are therefore dominated by their parent materials. The red colours and the presence of high proportions of sesquioxides should be attributed rather to rock-weathering than to profile development. In extreme cases the parent material and the soil horizons may be almost entirely sesquioxidic. Such soils are termed lateritic. Laterites may originate also in other ways, and no subject has been more actively discussed and investigated during the past thirty years than the laterite problem.

The general character of tropical red soils may be briefly reviewed. They occur in humid climates under forest, jungle, or savannah. Owing to the intense evaporation, the soil is more completely dried out between rains than is the case in temperate climates. This probably accounts for the frequent occurrence of concretionary deposits of varying sizes. The base-status is very low, but the reaction as measured by *p*H is frequently not so low as might be expected, a circumstance attributable to the sesquioxidic character of the clay complex. Unlike soils of colder climates, where *p*H generally increases with depth, tropical soils often show their highest *p*H at the surface. There is no marked chemical eluviation and the structure is generally friable and granular. In these respects they resemble the brown earths. On the other hand, the great stability of structure usually hinders mechanical eluviation.

Prairie Soils

The soils with completely leached profiles are developed typically under forest, scrub, or heath. There is one group of soils, however, with completely leached profile but occurring under tall grass vegetation. These soils, which have been studied mainly in the United States, are dark-coloured soils with a high organic matter status. Their base-status is also high, but there is no free calcium carbonate in the soil profile and they are therefore slightly base-unsaturated. They are the least intensively leached of the soils of the major group and occur along the dry boundary of the leached soils. On account of their high base-status there is no breakdown of the clay complex and no appreciable free ferric oxide in the profile. They have a good granular or crumb structure and they are distinguished from the tshernosems on the other side of the humid-arid boundary by the absence of an horizon of calcium carbonate accumulation. Otherwise, they show considerable resemblances. Agriculturally, they are naturally very fertile. Some of the best soils in the United States, occurring in Iowa, belong to this group. They are found also in Argentina, and tropical variants probably occur also in Africa and in Brazil.

Grassland soils in England have many affinities with the prairie soils. They have a high humus status, and if well managed, a high base-status, and good structure. It should be realized that these characters are due to human interference. Under natural conditions, they would tend to become brown earth or grey-brown podsolic soils under forest, with a correspondingly low base-status.

Incompletely Leached Soils

These soils, for which Marbut proposed the term *pedocals*, are developed in semi-arid climates under steppe to desert vegetation, and differ fundamentally from the leached soils above described. They form a succession from tshernosems to desert soils.

Tshernosem

This Russian word signifies black earth. As a group, the tshernosems have been intensively studied in Russia and North America. They occur in a semi-arid climate under a natural vegetation of short grass prairie or steppe, being typically developed in the Ukraine, and in North America in parts of Kansas, Nebraska, the Dakotas, Manitoba, and Saskatchewan. They are characterized by a deep humic layer, usually from 70 to 100 cm. in thickness, with an organic matter of 10 to 12 per cent., rising in some cases to 16 per cent. Their colour is typically black, but dark browns are also seen. The structure is granular and very stable. The base-status is high, but the upper horizons are free from calcium carbonate. In the lower horizons, generally below the humic horizon, there is invariably an horizon of calcium carbonate accumulation ; below this may be an horizon in which gypsum is deposited, but this is not an invariable character. The clay complex is stable and there is no liberation of sesquioxides.

The calcium carbonate horizon varies in thickness and mode of development. Towards the humid boundary of the group, i.e. where the tshernosem passes into the group of leached soils, the deposition is scanty and may take the form of a mealy deposit on the structural elements, or may appear as threads resembling the mycelium of a fungus. Where it is more definitely developed, it may be in the form of concretions, which are often hollow and assume curious forms. Another characteristic feature of tshernosems is the occurrence of *krotowinas* in the humic horizon. These are formed by the deposition of calcium carbonate in the burrows and tracks of steppe animals.

Under agriculture, the tshernosems are naturally of high fertility and some of the most important wheat-growing areas of the world are on them. They have, however, the disadvantage of being subject to drought, occurring as they do in dry climates.

In North America, they pass with increase in humidity into the prairie soils, which they closely resemble. The transition, however, is an important soil boundary, because it marks the change from soils of complete leaching to soils of incomplete leaching. This boundary runs roughly north and south from Minnesota to Texas. In Europe the corresponding boundary runs from north-east to south-west, through Southern Russia and the Balkan States. Here, the adjoining soils on the humid side of the boundary are different from the prairie soils of America. These soils, called *degraded tshernosems*, appear to originate through the invasion of the steppe by forest. They show the bleached surface horizon like the podsols, and sesquioxide deposition in the lower horizons. At the same time they retain vestiges of the original tshernosem structure. They must be grouped with the leached soils.

Chestnut Earths, etc.

Passing from the tshernosem region in the direction of increasing aridity, a corresponding change takes place in the character of the profile. The content of organic matter decreases and the humic horizon becomes thinner. Parallel with this change, the calcium carbonate horizon becomes better developed and approaches more closely to the surface. The vegetation becomes more sparse, until it ceases to form a closed association, the final stage being desert. Chestnut earths, brown semi-desert soils, grey semi-desert soils, and desert soils are stages that have been recognized in this transition

Tropical Analogues of the Tshernosem Succession.

In the foregoing account, we have been discussing soils of temperate regions. In tropical regions, a similar succession may be observed, differing in certain respects from those above described. They have a lower organic matter status, and show warmer colours, presumably owing to the presence of free ferric oxide. The final member is red desert soil, which may be contrasted with the grey desert soils of higher latitudes. The transition may be well observed in passing from the grey sagebrush desert of Utah to the red desert of southern California.

Soils with Impeded Leaching

Contrasted with the freely drained soils are the soils developed under conditions of impeded drainage. Here the profile is for a part or the whole of the year waterlogged with the consequent prevalence of anaerobic conditions. Even in humid climates the leaching is less intense than in the freely drained soils. Anaerobic conditions favour the accumulation of organic matter, but since root development is restricted, there is a sharp transition from humous top soil to raw subsoil. Greyish colours predominate owing to defective oxidation, but in the upper part of the profile, where conditions alternate between oxidizing and reducing, hydrated ferric oxide is deposited on the surfaces of the structural elements in an irregular fashion, giving characteristic mottling or streaking. Other secondary deposits include gypsum, manganese dioxide, and calcium carbonate.

By some writers, soils with impeded drainage are not considered to form a major group, but are regarded as local phenomena. In view of their world-wide occurrence under all types of climate it would appear necessary to make them a major category. They may be subdivided according to the presence or absence of sodium salts in the profile, the former sub-group occurring mainly in arid climates.

Gley Soils

These are soils developed under conditions of impeded drainage without accumulation of peat. The natural vegetation consists of grasses, rushes, sedges, and moisture-loving herbaceous plants. Trees such as alder and willow may also be present. Leaching is sluggish and the base-status is generally higher than that of adjoining soil with free drainage. In many cases, gley soils are enriched by mineral constituents leached out from soil lying at higher levels. This may be well seen in the relatively rich herbage of " flushes " in upland regions. Owing to the prevalence of reducing conditions, the ground colour of gley soils is generally greyish, but the alternation of oxidizing and reducing conditions in the zone of fluctuation of the ground-water level results in the deposition of hydrated ferric oxide. This deposition is localized and gives rise to a mottled or streaked appearance, quite distinct from the more uniform precipitation of ferric oxide in the B-horizons of podsols. Soils of this class also show rusty deposits along the channels of plant roots in the turf layer. The horizon of maximum deposition of ferric oxide is called the *gley* horizon. By gleying is understood not only the deposition of ferric oxide, but also the development of a characteristic thin glaze or coating on the surfaces of the structural elements. This coating consists of fine clay particles deposited from the turbid soil water in the interstices between the structural elements.

Typically, the profile consists of a comparatively shallow surface horizon, rich in humus and having a crumb or coarsely granular structure. The mineral colour is grey, but rust markings are seen along root channels. There is a fairly sharp transition to raw subsoil, due to the restriction of root development, and the relatively scarcity of earthworms. The structure of the sub-surface horizons is generally massive and tending towards a columnar structure. Rusty streaks and mottlings are abundant near the water-table and the varnish-like glaze on the structural elements may be seen if the profile is allowed to dry out and carefully disintegrated. Occasionally, deposits of gypsum or calcium carbonate are found in the gley horizon. Streaks or soft concretion of manganese dioxide may also be present. Below the lowest level of the ground water, the conditions are permanently reducing and the colour of the soil is grey or bluish-grey owing to the presence of ferrous compounds.

There are many varieties of gley soils, but a simple subdivision may be made into soils affected by a high regional water-table, and soils in which drainage is impeded by an impervious subsoil. Soils of the former class show the best developed gley horizons. They are permanently wet in the lower horizons and can have all textures from sands to clays. The other class of soils, where drainage impedance is caused by an impervious subsoil, may occur in both lowland and upland situations. The water-table is less definite than in the other class and gley horizons are not so clearly developed. Instead there is a diffused mottling or streaking with iron oxide throughout the profile. During the summer the soil profile may dry out to a great extent and crops growing on them may suffer from drought, as may be seen on many of the clay formations, such as the Gault of Southern England.

Gley soils vary considerably in fertility. With a controlled water-table, those of the first class, as in the alluvial soils of the Fen district, may be exceedingly fertile. They occur in lowland flat situations, and, apart from a tendency to frost, lend themselves to intensive agriculture or horticulture. The soils of the second class include most of the clay formations of England, such as the Gault and the Kimmeridge clays. When well drained, they are fairly fertile as grasslands and can grow good wheat and beans. Owing to their heaviness and wetness, most of these soils were in grass at the beginning of the present war. With the advent of the tractor and the possibility of mole draining, these soils have been shown to possess considerable possibilities. Yet, however much may be done to improve tillage methods by the use of mechanized methods, clay farming will always demand the highest skill on the part of the cultivator.

Soils with impeded drainage occur in many parts of the tropics. Here, except in regions of tropical rain forest, dry seasons result in the complete drying out of the soil. The soils thus developed, often called *vlei soils*, resemble the gley soils of temperate climates by their grey or black colour and the occurrence of secondary sesquioxide deposits in the gley horizon. These deposits, as a consequence of the intense drought, often become indurated to form hard rock-like deposits.

Peat Soils

These are soils developed under conditions of excessive wetness, in which the humified residues of vegetation have accumulated to such an extent as to give predominantly organic soils. There is no hard and fast definition of peat, but when the organic matter content amounts to more than 20–25 per cent., it dominates the character of the soil and the soil may be described as peaty. With more than about 50 per cent. of organic matter the soil may be described as a peat.

There are many different kinds of peat, but the most important distinction is between lowland or lacustrine peat and upland or moss peat. The former type of peat is formed by the accumulation under water of the residues of lacustrine plants such as reeds and sedges, and is dominated by the influence of ground-water. The other type is found in more elevated situations, mainly from the residues of mosses and such plants as cotton grass, scirpus, etc. Often, but not invariably, there is a complete succession from lacustrine to moss peat.

Lowland peat, lacustrine peat, or fen peat is formed by the filling up of lakes or meres with the residues of aquatic plants. The process may be seen taking place in many lakes at the present day, particularly in Wales and Scotland. The peat of the English Fens was formed in this way. The ground-water has generally a fairly high mineral content and this is reflected in the character of the resulting peat, which, after drainage and reclamation, gives rise to soils of high productivity. On the other hand, where the ground-water is poor in bases, as in many mountain regions, the peat is potentially much less fertile and resembles the poorer moss or upland peat.

With continued accumulation of peat, the surface rises above the level of the original water surface and the vegetation undergoes a change. In some cases, trees may become established, but these only mark a transition stage and eventually they are replaced by mosses such as sphagnum. These have a high capacity for water retention and the conditions in the profile, instead of being dominated by the relatively mineral-rich ground-water, are dominated by water received by rainfall. There is thus a fall in base-status and an entirely different type of peat develops. This is known as upland peat, high-moor peat, moss peat, or bog peat. It is exceedingly poor in minerals and, even when drained, is only of low productivity. Reclamation is costly, because, not only must the peat be drained, but it must also be given lime, phosphate, potash, and even nitrogen.

The complete succession from lacustrine to moss peat is not always met with. In Scotland and Wales there are many tracts of peat in which only the second or high-moor stage is represented. In climates with high rainfall and constant high humidity, peat tends to accumulate in all but the driest situations.

Peats may develop from podsols. The B-horizon may become so dense that drainage is impeded. The profile then becomes successively a gley-podsol, a peat-podsol, and ultimately a peat.

Peats should be clearly distinguished from soils developed with free drainage under coniferous or heath vegetation. These soils have a humous surface layer, sometimes described as heath peat or forest peat, respectively. They are different in character from true peats, which are formed under the anaerobic conditions associated with excessive wetness. For such soils, or soil horizons, the term raw humus is more correctly applied.

Saline, Alkaline, and Soloti Soils

These soils may be considered together because they all owe their characteristic features to the presence of sodium salts, chloride or sulphate, in the soil profile. These salts may be the unleached products of weathering in arid climates, they may be left in the soil around the margin of an inland sea, such as the Caspian or the Dead Sea, or they may originate from saline ground waters.

Saline soils are soils in which there is an excess of sodium salts. Since these salts are deposited on the surface as a white efflorescence when the soil dries out, they are called in the United States *white alkali soils.* The excess of salts keeps the soil in a flocculated or granular condition, but is harmful to the growth of most economic crops.

Closely associated with the saline soils are the *alkaline* soils. These are derived from saline soils by the removal of excess sodium salts. When this takes place, the soil, which has been converted to a mainly sodium soil by the excess of sodium salts, undergoes hydrolysis, which may be illustrated in its simplest form by the equation :

$$\text{Na-Soil} + H_2O = \text{H-Soil} + NaOH$$

The sodium hydroxide is rapidly converted to sodium carbonate by reaction with atmospheric carbon dioxide. The liberation of sodium hydroxide or sodium carbonate results in the soil reaction becoming strongly alkaline. This causes the soil to deflocculate or disperse, thereby becoming impervious to drainage. The structure change involves a decrease in pore space and, consequently, areas affected are slightly depressed below the level of surrounding saline soil. This, and the hold-up of drainage leads to the formation of shallow pools after rain. The standing water, being alkaline, dissolves out humus from the soil as dark-coloured sodium humate. On drying, this is left as a dark or black varnish on the surface. Hence these soils are called in the United States *black alkali soils*. They are highly infertile on account of their strongly alkaline reaction, often above *p*H 9·0, and partly on account of their compact impervious structure.

In the absence of calcium carbonate, alkaline soils may undergo a further change. Hydrogen soil is formed as a result of hydrolysis, and when the liberated sodium hydroxide or carbonate is removed by drainage, the reaction of the soil becomes acid. When this stage is reached a degradation takes place analogous to podsolization, resulting in the development of a bleached A-horizon and the deposition of sesquioxides in the B-horizon. The resulting soil is called a *degraded alkali* or *soloti* soil.

Saline, alkaline, and soloti soils occur in closely associated complexes in regions of low rainfall, as in regions of tshernosem or chestnut earth soils. They may also be developed where irrigation is practised in dry climates, particularly if the irrigation water contains an excess of sodium over calcium. The degeneration of irrigated lands by salinization and alkalization is accentuated where no drainage system has been provided. In many parts of the world, notably in Mesopotamia, there are vast areas of derelict land that once carried a flourishing irrigated agriculture.

Soil Surveys

Soil surveys are in progress in most civilized countries. The object of a soil survey is to produce a map of the soils of the country. This would be a fairly straightforward task if soils fell into easily recognizable classes analogous to the genera and species of plants and animals. But soils do not fall into such well-defined categories and it is not always easy to decide what basis shall be used for mapping. The material and human resources available for soil survey are limited and some compromise has to be sought between great accuracy with slow progress on the one hand, and rapid progress with low accuracy on the other.

The time taken to produce a soil map of an area varies enormously. It depends on the actual variability of the soil and also on the degree of detail required. For some purposes, e.g., where intensive utilization is contemplated, it may be necessary for a worker to spend a month in mapping a few hundred acres. On the other hand, where a rapid reconnaissance is all that is required, several hundred square miles might be covered in the same time.

It is obvious that for a soil map to be of use to farmers and others, it will not be sufficient to distinguish only such classes as podsols, brown earths, etc. A very considerable proportion of the soil of this country would be classed as brown earths, but within this group, there would be important differences depending on depth of soil, kind of parent material, texture, etc., which would be very important in practice. A closer subdivision is therefore necessary.

In this country and in most countries of the British Empire, the *series* classification, first worked out in the United States, is used as the basis of soil surveys. A *soil series* is a group of soils showing the same or similar succession of horizons in the profile and developed from the same or similar parent material. Soils of the same series will have essentially the same colour, structure, and other internal characteristics. Some variation in texture is permissible, but heavy and light soils should never be grouped in the same series. Soil series are given names after places where they were first studied or where they occur commonly. For example, Arvon, Penrhyn, and Flint are names of soil series found in North Wales. They may also occur in England and, possibly, Scotland. Similarly, series such as Salop, Newport, and Worcester originally found in England may occur in Wales.

Within the soil series are *types*, defined according to texture. Thus, within the Penrhyn series, we may have Penrhyn light loam, Penrhyn medium loam, and Penrhyn silty loam.

Finally, types may be subdivided into *phases*, depending on relief and depth. We may have, for example, in the Penrhyn medium loam a rolling phase, a steep phase, a shallow phase, and so on. Such distinctions may be important for particular purposes. In the first stages of soil survey, however, only the soil series will be distinguished.

For ordinary routine mapping in Great Britain, the 6-in. to the mile Ordnance Survey map is used as the base. For intensive mapping of small areas for special purposes, the 25-in. to the mile map may be used, whilst reconnaissance may be made on the scale of 1-in. to the mile. The surveyor works systematically across his area, checking the uniformity of the soil by frequent auger borings. Having satisfied himself as to uniformity, he will then open up a trench or pit at a typical site and make a profile description which is recorded on a standard sheet. Data are recorded always under the following headings :

A. Site characters.
B. Parent material.
C. Vegetation.
D. Profile characters. Depth and succession of soil horizons with data for each horizon on
    1. Texture.
    2. Colour.
    3. Structure, compaction, and stoniness.
    4. Organic matter.
    5. Presence of secondary deposits, e.g., MnO_2.
    6. Root penetration.

A. The site characters include elevation, aspect, and regional drainage, together with any available climatic data.

B. The data on parent material include the lithological character of the unweathered rock if the soil is sedentary, and the character and provenance of the drift if it is a transported soil. The latter information is not always easily ascertained, particularly in the case of mixed drifts.

C. The general character of the vegetation, e.g., whether forest, grassland, heath, or scrub, should be given and the dominant species listed. If in cultivation, the cropping should be given.

D. The profile character should be described after the horizons have been distinguished. In giving the depths of the horizons, it should be stated whether the boundaries are clear, merging, or indefinite. Detailed instructions for profile descriptions are given in G. R. Clarke's *Study of Soils in the Field.*

Soil boundaries are discovered by auger borings. Frequently they are indicated also by changes in topography or by natural vegetation. In some cases there is no sharp boundary between one series and another and the boundary must be shown as a broken line. Another difficulty in mapping is the occurrence of a complicated pattern of two or more soil series or types, as in certain alluvial and drift areas. Where time does not suffice for the accurate delineation of all boundaries, it is necessary to map the area as a complex. The nature of the complex may be indicated by a description of the soil present, giving a detailed map of a specimen small area.

From time to time profile samples are taken for analysis. The following data are necessary for each horizon.

1. Mechanical composition.
2. Organic matter and nitrogen.
3. Composition of the clay fraction.
4. Base status, including $CaCO_3$, if present, *p*H, and exchangeable bases.
5. Soil colour after removal of humus.
6. Soluble salts, if present.

An example of a 6-inch map of an area in Anglesey is given in Fig. 22. For simplicity, roads and topographical features are omitted, although they are present on the actual soil maps, because these are made on the 6-inch Ordnance Survey sheet. Numerous manuscript notes are made on the map to indicate local variations and peculiarities.

A necessary adjunct to the soil survey is the collection of

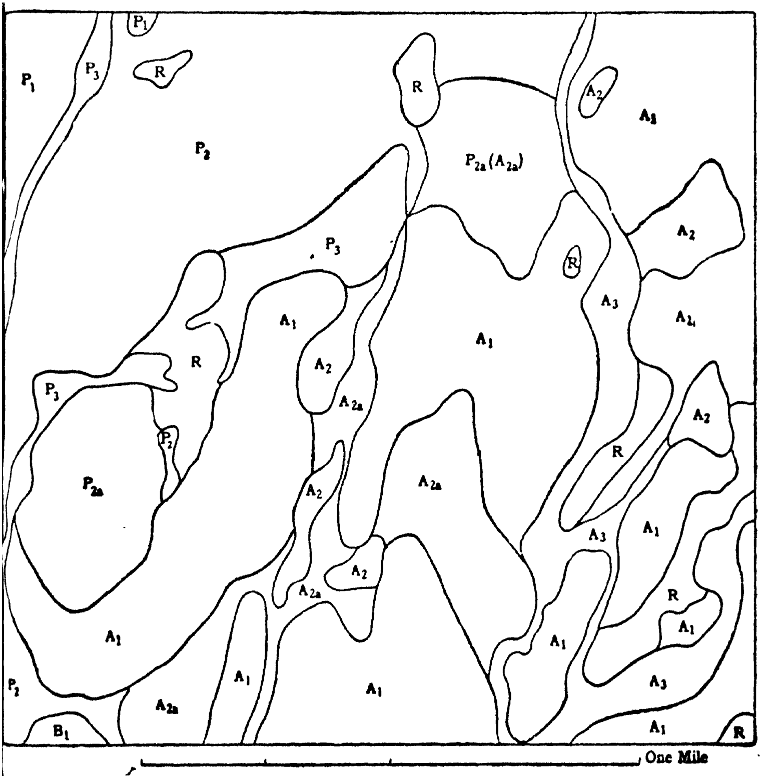

Fig. 22.—Portion of Soil Map of Anglesey.

A_1. *Arvon* series. Well-drained, fairly deep, light stony loams, derived from acid crystalline parent material. A_2. *Eivion* series. Poorly drained loams, rather shallow, derived from similar parent material. A_3. *Ynys* series. Wet alluvial soils from similar parent material. A_{2a}. *Eivion* series (improved). Similar to Eivion but improved by drainage.

P_1. *Penrhyn* series. Fairly deep, well-drained loams, derived from shale or mudstone parent material. P_2. *Cegin* series. Poorly drained, medium to heavy loams, derived from similar parent material. P_{2a}. *Cegin* series (improved). Similar to Eivion but improved by artificial drainage. P_3. *Conway* series. Wet alluvial soils, derived from similar parent material.

R. Thin soils with rock outcrops.

monoliths. A monolith is an undisturbed column of soil profile showing the natural structure and arrangement of the horizons. It is obtained by excavating a trench and exposing three sides of a vertical column of soil. A sheet-iron box is then fitted to it, and the fourth side is then cut away leaving the soil profile in the box. After the monolith is brought to the laboratory, the face is carefully picked clean in order to expose the natural structure.

Soil Surveys, Productivity-Ratings, and Land Classification

The actual agricultural use of a given piece of land depends on a number of factors, namely (1) the character of the soil profile ; (2) the site characteristics, including climate, situation, and aspect ; (3) economic factors ; (4) past history. The importance of the soil itself is obvious. The more spectacular effects of climate and situation are also obvious, but even minor variations may have important consequences for agriculture. A southern slope, freedom from frost, and abundant sunshine may render possible the development of specialized cultures, such as market gardening, in close proximity to situations where only mixed agriculture is possible. Economic factors include access to markets, labour supply, etc. With improvement of transport, these considerations should be of less importance. Behind all, however, is the overriding influence of national and international economics. We have seen how, during the present war, thousands of acres have been diverted from grass to arable. Under the heading of historical factors we may include such circumstances as the actual character of the population, e.g., the propensity of the Welsh farmer to pastoral rather than to arable husbandry, systems of land tenure affecting the size of holdings, and even such apparently casual factors as estate management and the example of good farmers.

From these considerations it is clear that a soil map cannot be expected to be an accurate reflection of agriculture as it is, or as it may be. The soil map must be considered in conjunction with all other relevant available information. Yet, since the most favourable conjunction of climate, situation, economics, and history, cannot offset the disadvantages of an inherently poor soil, a knowledge of the distribution of the different kinds of soil is indispensable for the planning of future agricultural development, and for the investigation and solution of the problems of present agriculture.

A soil map with its explanatory memoirs should place on record the maximum of information about the physical facts connected with the soil. It cannot be claimed, however, that it is immediately translatable into terms of land use. Much study is needed before the agricultural potentialities of each soil category can be listed. In order to obtain such a correlation, not only must a satisfactory soil classification be elaborated, but a satisfactory system of productivity-rating must be established. A considerable amount of work has been carried out in the U.S.A. on productivity-ratings, but up to the present it cannot be claimed that any generally accepted system has been devised, although many have been proposed. The official method of the Bureau of Soils is based on actual crop yields expressed as a percentage of estimated maximum yields. Uncertainty is introduced by the arbitrary weighting of the various crop indexes and by the choice between actual yields with and without soil improvements such as drainage and the use of artificial fertilizers. Indeed, the whole question of soil fertility is intimately bound up with the extent to which skill is used. Changes in agricultural technique may profoundly modify the relative productivity of different categories of soil. For example, the general adoption of liming would raise whole areas of soil in the west from low into high fertility grades. Similarly, drainage or irrigation can result in spectacular increases in productivity. From what has been said, it is evident that the quantitative assessment of soil fertility is a difficult and hitherto unsolved problem. It is equally certain that even if soils could be arranged into fertility classes, such an arrangement would be liable to profound modifications through changes in agricultural technique.

Whilst any exact assessment of soil fertility is beset with serious difficulties, it must be admitted that gross differences in productivity between different kinds of soil can be discerned. It should be possible to place an approximate value on the different soil classes distinguished in the Survey, although it is recognized that there is no absolute standard of soil fertility. The value of a soil depends on the purpose for which it is used and the extent to which skill is employed. A soil that shows only low productivity under poor farming may be very fertile under skilful farming.

Land classification has been defined[1] as the grouping of land into classes according to its capability and desirability for agricultural use. Land classification is both wider and narrower than soil classification. Soils belonging to different categories may be similar from the standpoint of agricultural use, whilst, within a single soil category, externalcharacteristics such as climate, altitude, aspect, and surface relief, may have important consequences for actual utilization. In many cases soil classification and land classification may be identical.

It is very necessary to distinguish between the capacity of a given soil for a particular use and its feasibility for such a use. The soil surveyor may indicate on his map a certain soil as suitable for the growth of certain crops, but it does not follow that such would be the optimum use. Both the actual use of the land and its optimum use depend on a number of factors, of which the soil is only one, even if it is the dominant factor. So far as actual use is concerned the relevant factors are:

(1) Soil and climatic conditions.
(2) Economic conditions.
(3) Past history.

The historical factors should be stressed because there is a danger of taking too deterministic a view of land use. Land use is not simply the integration of soil and economic factors. The influence of a landowner or even of a prominent farmer may change the whole aspect of the agriculture of a district, although within the limits appointed by soil, climate, and economic conditions.

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[1] Professor H. H. Krusekopf, "Land Classification in relation to the Soil and its Development," in *Bull.* 421, Univ. of Missouri, College of Agriculture, 1940.

Soil maps are already being used in connexion with plans for post-war development. Their chief use in this connexion is to assist in indicating, on the one hand, areas where the soil is so good that it should be, if possible, reserved for agriculture or horticulture and, on the other hand, areas where the soil is of inferior character and can thus be released for urban or industrial uses. Naturally, there will be many cases where the best agricultural land is also the most desirable for non-agricultural development. Here it will be necessary to treat each case on its merits with a thorough consideration of all the factors involved.

The development of soil research is very necessary in the interests of efficient agriculture. This includes the setting up of large numbers of field stations and the laying down of still larger numbers of plot experiments. In the selection of these experimental sites, the soil survey should be taken into account. As far as possible, experiments should be located on all the important soil types. As an invariable rule the data provided by any field experiment should include information as to the series and type of soil on which the results have been obtained.

CHAPTER XI

THE ANALYSIS OF SOILS

Sampling—Determination of Plant Nutrients—Organic Matter and Nitrogen—Mineral Constituents: Phosphoric Acid; Potash—Determination of Base-status—Soil Analysis by the Plant—Leaf Diagnosis of Nutrient Deficiencies—Uses and Limitations of Soil Analysis.

THE immediate object of soil analysis is to ascertain the amount which the soil contains of the various elements necessary to the nutrition of plants, with view of either making good the general deficiencies of the soil or of adjusting the supply of plant food to such special requirements of a particular crop as may be indicated by previous experiment. A further object may be to obtain an accurate characterization of the soil for the purposes of soil classification and soil survey.

Sampling of Soils

The first step in the analysis of any soil consists in obtaining a sample that shall accurately represent the land in question. All soils show considerable variation and a sample taken from one point in a field may give a misleading impression of the character of the field as a whole, if the object is to obtain an assessment of the requirements of the soil for plant food constituents in the form of manures and fertilizers. In such cases it is therefore customary to take samples from a number of different points in the field, and to unite these to form a composite sample. The number of samples thus taken to form the composite will vary with the degree of accuracy desired. As a general rule about 20 samples would be taken from a ten-acre field for routine advisory purposes. On the other hand, where the object is to make a critical study for the purpose of classification or survey it is usual to dig out a pit at one point and sample the profile, horizon by horizon.

For advisory purposes, it is customary in this country to take a sample down to a depth of 9 inches as representing the soil proper, but this is probably too deep, being below the depth to which cultivation is usually carried ; probably a 6-inch sample would more truly represent the cultivated soil. For old grassland soils an even shallower sample might be taken. Where there is a sharp change in the character of the soil above the usual depth of sampling, the sample should be taken to this depth. For example, on the chalk downs the change from soil to subsoil may occur at not more than 4 inches. On the other hand, in certain intensively farmed soils such as the silt loams of the Holland division of Lincolnshire, the soil proper may extend to 12 inches or more.

To obtain the sample, two methods have been adopted.

At Rothamsted, a steel box without top or bottom, 9 inches deep and 6 inches square in section, is used. The sides are wedge-shaped, about ¾ inch thick and tapering to cutting edges below. The surface, if uneven arable land, is first raked over and gently beaten level. The box is placed in position and driven down with a heavy wooden rammer till the top of the box is flush with the surface. The soil enclosed by the box is then carefully dug or scraped out and placed in a bag for conveyance to the laboratory, two or three samples being taken from the same field and afterwards mixed. Should samples of the subsoil be required, the box is left in position after its contents have been removed, the surrounding soil is dug away to the 9 inch level, and the box is then rammed down for the second 9 inches, after which the sample is taken as before.

For routine advisory work it is more usual to take samples by means of the auger method. Two types of augers are in use. The one type consists of a cylinder of steel about $\frac{1}{16}$ inch thick, of 2 inches internal diameter, and about 12 inches deep, with a slot ¾ inch wide running from top to bottom ; the lower edge of the cylinder is sharpened to a cutting edge to the upper end, a handle carrying a wooden crossbar is riveted. The auger is forced gently into the soil with a twisting motion until the required depth is reached, when the tool is withdrawn and the core scraped out into a bag. In heavy soils, two or three " bites " may be necessary to reach the necessary depth. The other type, which is much more commonly used, consists of a 1-inch or 1½-inch post auger fitted to an iron rod with a cross handle. This can be screwed directly into the soil. The disadvantage is that in dry weather the soil falls off the auger. In such cases, the cylindrical auger or the box sampler may have to be used. As the amount of soil brought up by one one-auger boring is small, there is no difficulty in taking a large number of samples to make the composite, and from 10 to 20 are commonly taken.

A word of caution is needed about the taking of composite samples. In large fields more than one type of soil may be encountered. For example, in the upper part the soil may be a light well-drained loam, whilst in the lower ground the soil may be a wet clay. In such cases separate samples should be taken of each type. Where more than one crop is grown in a field or where it is known that more than one treatment has been followed, it is necessary to take a sample for each parcel.

When the samples reach the laboratory they are spread out on shallow trays to dry, which process may be accelerated by a gentle warmth, not exceeding 40° C. In dealing with stiff soils it is advisable to crumble all the lumps by hand whilst the earth is still somewhat moist. When the whole is sensibly dry the stones are separated by a sieve having round holes 2 mm. in diameter ; the material that does not pass the sieve is gently worked up in a mortar with a wooden pestle, care being taken not to break the stones, chalk, etc., but only to crush the lumps of earth. Finally, the material upon the sieve is roughly weighed and well washed in a stream of water till all the fine earth is gone, dried, picked over to free it from roots and stubble and weighed as " stones." To get the proportion borne by the stones to the soil, the fine earth also is weighed, an addition being made of the weight lost by the stones in washing.

Of course the figure obtained for the proportion of stones is only approximate, for if the stones are of any size they will be very irregularly caught by the auger or even by the 6-inch square tool. The material passing the sieve is again spread out in a thin layer in an ordinary room, until the surface attains the same colour as the lower layers ; it is then bottled up as " air-dry fine earth " for analysis.

Determination of Plant-Nutrient Deficiencies

The analysis of plants grown under ordinary conditions shows that a comparatively limited number of elements enter into their composition : in the main they are composed of water and certain combustible compounds of carbon, hydrogen, nitrogen, and sulphur. In the mineral residue that is left after the combustible matter has been burnt off will be found potassium, sodium, calcium, magnesium, and a little iron as the principal bases ; and phosphorus, chlorine, sulphur, and silicon as the principal non-metallic elements. Manganese in very small quantities occurs in all plants : other elements, notably iodine, boron, copper, zinc, and cobalt are also found, and have been shown to be necessary constituents. The list of essential elements is continually being added to and many defects of plant and animal nutrition have been shown to be due to insufficiency or low availability of these "trace" elements.

By pot culture in the laboratory, it can be shown that of the above elements, the carbon, hydrogen, and oxygen are drawn from the atmosphere or water, and that the remaining elements are derived from the soil by way of the roots and are necessary for normal growth and reproduction. The above list is certainly incomplete and further elements will doubtless be added to those at present known to be essential.

In view of the above facts it is clearly unnecessary to make an ultimate determination of all the elements present in the soil, which has been shown to consist largely of sand and various silicates of alumina, etc. These materials constitute the medium in which the plant grows, but do not themselves supply plant food.

So far, then, as soil analysis aims at determining plant nutrient status, it resolves itself into the determination of the nitrogen, phosphorus, potassium, and calcium, but for certain purposes, it may be necessary to determine other elements, including the so-called trace elements such as copper and boron. To these determinations may be added the determination of the carbon compounds of the soil, already mentioned under the head of humus, and the base-status of the soil as an indication of the lime requirement.

Having decided upon the elements to be determined it would then be possible to proceed as in an ordinary mineral analysis : the sample of soil would be finely powdered and then entirely disintegrated by fusion analysis with fusion mixture or ammonium fluoride. But results obtained in this way would give very imperfect information, for the procedure draws no distinction between material present in the stones and larger particles and that existing in minute particles and therefore open to attack by the soil water. The nutrient material of the soil can reach the plant only in the dissolved state, and in dealing with slightly soluble substances such as constitute the soil, the amount which goes into solution is practically proportional to the surface exposed. Hence it becomes necessary in soil analysis to accept certain conventions as to the preparation of the soil for analysis, the nature of the reagent used for solution, and the duration and temperature of the attack, as well as the ratio of the soil to reagent used. It must be remembered that soil analysis is only a relative process, by which soils that are unknown are compared with each other, and with soils whose fertility has been tested by experience. No means exist of translating the results into terms of the crop the soil will carry. Unfortunately there is no uniformity in the methods used in different countries, or even in all methods used by agricultural chemists in our own country.

Organic Matter and Nitrogen

Given the importance of organic matter in the soil, it might be thought that the determination of organic matter would be made in all routine soil analyses. Actually, this is not the case. Until recent years the loss on ignition was determined and assumed to give an indication of the amount of organic matter present. Indeed, in many of the older analyses, figures obtained by loss on ignition were wrongly shown as organic matter. When an oven-dry soil is ignited in air the loss in weight includes not only the organic matter burnt off, but also water chemically combined with the clay. In soils containing calcium carbonate there is also a loss due to carbon dioxide driven off at bright red heat.

No satisfactory method exists for the direct determination of organic matter. Digestion with 30 per cent. hydrogen peroxide removes most of the organic matter, and the loss in weight after this treatment will give an approximate, but rather low, result. The usual method is to determine the percentage of organic carbon either by dry or wet combustion and to multiply the figure thus found by the conventional factor 1·724. The use of this factor is based on the assumption that soil organic matter contains 58 per cent. carbon. This figure has been obtained from the study of peats and is not necessarily accurate for the organic matter of ordinary soils. A further error in determining the organic matter from the organic carbon figure is introduced if much carbon is present in the form of fragments of coal or cinder, as is the case with many soils. Nevertheless, in the present state of knowledge, organic carbon is the most trustworthy basis for the determination of organic matter in the soil.

The inaccuracy of " loss on ignition " as a measure of soil organic matter may be seen from some typical comparisons :

Soil.	*Organic Carbon.*	*Organic Carbon. × 1·724*	*Loss on Ignition.*
Loamy sand . . .	2·4	4·1	5·2
Sandy loam . . .	3·7	6·4	9·0
Medium loam . . .	4·3	7·4	9·5
Heavy loam . . .	5·1	8·8	12·4
Heavy subsoil clay . .	0·7	1·2	10·7

In British agricultural soils the proportion of organic matter varies from 2 per cent. or less in light sandy soils to 10 per cent. or more in old pasture soils in the humid districts of the west. The usual range is from 4 to 7 per cent.

Nitrogen is usually determined by the Kjeldahl method. During recent years, this determination has fallen out of routine practice. Since by far the greater part of the nitrogen present in the soil is in forms unavailable to plants, a determination of total nitrogen can give little indication of the need or otherwise for nitrogenous manuring. The nitrogen content may be of some use as an indication of the organic matter content. In ordinary British soils the ratio of carbon to nitrogen approximates to 10. Wider ratios are found for peats and heath soils. The significance of the ratio even among soils of the same general type is not clearly understood.

Attempts have been made from time to time to devise methods for determining the nitrogen in forms available to plants. Plants normally take up their nitrogen as ammoniacal or nitrate nitrogen, and it might be thought that a determination of the amount of nitrogen present in these forms would give a measure of nitrogen availability. Whilst soils in very high condition may contain considerable amounts of nitrate, perhaps up to more than 100 parts per million, the ammoniacal nitrogen is not more than a few parts per million, except in acid soils. The amount of nitrate nitrogen is also subject to very great fluctuations even in the same soil. The same field sampled at a few hours' interval might give very different values for the amount of nitrate nitrogen. These determinations have thus proved of little value for assessing the available nitrogen status of soils. Methods have been proposed based on the determination of the nitrogen extracted by weak acids, but they have not come into general use.

Mineral Constituents

By mineral constituents in this connexion are understood only those elements of plant food likely to be present in soils in insufficient amount for the needs of crops. In practice, this generally means phosphoric acid (P_2O_5) and potash (K_2O). There are, of course, other elements that may occasionally be deficient, but their determinations have not as yet become part of routine soil analysis.

Phosphoric Acid.—The total phosphorus of soils may be determined by total fusion or by digestion with sulphuric and nitric acids. Phosphorus is present in the soil in apatite minerals, in aluminium and ferric phosphates, in organic compounds such as nuclein and lecithin, and combined with the clay-humus complex. There may be present also small amounts of dicalcium phosphates, $CaHPO_4$, particularly in soils recently dressed with superphosphate. Of these forms, the calcium compounds, including the apatite minerals, are the most available, but much depends on the physical condition as well as on the chemical combination in which they occur. For example, when using tribasic phosphates of lime as manures, the softer phosphates such as steamed bone flour are more effective than the chemically similar but harder material in certain ground rock phosphates. Almost invariably phosphoric acid is less abundant in the subsoil than in the surface, where it has been accumulated as a residue from the decay of previous vegetation, and also, in some cases, from phosphate applied in manurial dressings.

The proportion of phosphorus, expressed usually as P_2O_5, varies considerably, the usual range being from 0·1 to 0·2 per cent. in British agricultural soils. Much lower figures are found in the soils of other countries. For example, in South Africa and Australia, figures down to 0·1 per cent. are often found. Higher figures for total P_2O_5 are found in market garden soils and in the soils of rich old pastures.

Since most of the phosphorus present in the soil is unavailable to plants, the figure for total phosphorus gives little information as to available phosphorus in the soil. It may, however, be of some value as indicating possible reserves of soil phosphorus.

As in the case of nitrogen, so in the case of phosphorus attempts have been made to devise methods for determining available phosphorus. Here, some measure of success has been attained. Most of the methods proposed are based on extraction with dilute acids.

The best known and most widely used of these methods is that of Dyer in which the soil is extracted with 1 per cent. citric acid. Before discussing this method, it may be helpful to make some observations on this type of analytical procedure, since most methods of determining plant nutrient status depend on extraction of the soil with dilute acid reagents.

Neither the citric acid method nor any of the other acid extraction methods extracts any definite category of soil phosphorus. When a particular method gives the available phosphoric acid as so much per cent., it must not be assumed that a hard and fast line has been drawn between the available or the unavailable phosphorus. Such a definite limit cannot be placed. In the soil there is a variety of compounds of phosphorus of varying degrees of availability to plants. All these compounds will have some solubility in a given extractant and the solubility of a given form of phosphorus will not necessarily reflect its availability to plants.

Methods such as the Dyer citric acid method are necessarily "conventional." That is to say, the conditions of extraction must be exactly specified. In the Dyer method 100 grams of soil are shaken with 1 litre of 1 per cent. citric acid at room temperature for 24 hours. A variation in any of these conditions will lead to a different result. Thus, an increase in the ratio of extractant to soil or a rise in the temperature of extraction will each be reflected in an increase in the amount extracted. The effect of time of extraction is irregular, but there would probably be little change if the extraction were continued with shaking for a longer period than the prescribed 24 hours.

We should regard the figure given by the Dyer method, or any similar method, rather as an index of availability than an estimate of the actual amount available.

For ordinary British agricultural soils the following standards may be used in assessing results by the Dyer citric acid method :

	mg. P_2O_5 *per cent.*
Very low	0–7
Low	8–11
Medium low	12–15
Medium high	16–20
High	20–30
Very high	30+

These standards need adjustment for different conditions. Thus, for highly organic soils and wet climates, the standards should be raised somewhat.

The data in the following table are of interest. They were obtained by the Dyer method on differently manured plots of the famous Broadbalk and Hoos fields at Rothamsted. The extraction was repeated in each case for five or six times.

The marked contrast between the plots receiving phosphate and those without phosphate will be noticed at once. The figures for the successive extractions show that not all the extra phosphate is removed in the first extraction. In the later extractions, the amount of phosphoric oxide sinks to a

Phosphoric Acid, Mgms. per 100 Grams Soil

Field.	Plot.	Treatment each Year.	Extraction.					
			1st.	2nd.	3rd.	4th.	5th.	6th.
Broadbalk	3	Unmanured	6·4	6·8	3·9	3·0	2·5	...
”	5	64 lbs. P_2O_5, no Nitrogen	69·0	28·0	11·3	7·3	4·5	2·3
”	7	64 lbs. P_2O_5, 86 lbs. N.	56·1	22·8	8·9	6·5	4·4	4·4
”	8	64 lbs. P_2O_5, 129 lbs. N.	46·3	18·9	7·8	5·3	4·0	3·0
”	10	86 lbs. N. only	7·7	5·2	3·3	2·7	2·7	2·7
”	2	Dunged	49·3	15·3	7·5	6·0	4·4	...
Hoos	1AA	43 lbs. N. only	6·3	3·5	2·2	1·9	2·0	1·2
”	2AA	64 lbs. P_2O_5, 43 lbs. N.	52·2	21·2	8·9	6·5	3·8	·9
”	3AA	43 lbs. N. and Potash	6·3	2·7	2·3	2·1	1·9	
”	4AA	64 lbs. P_2O_5, 43 lbs. N., Potash	53·5	10·6	6·4	4·9	4·5	3·8

low figure, representing the solubility of the less soluble phosphorus compounds of the soil. If the extractions had been continued, the amount extracted each time would be approximately constant at this low figure.

Potash.—It is not easy to classify the various compounds of potash present in the soil: we know that in the weathering of potash felspar, there are intermediate stages of weathering in which the potash becomes progressively more soluble. Exchangeable potash appears to form a definite category; but there is evidence that this does not represent the whole of the potash available to plants. It appears that there is also a category of available but non-exchangeable potash. Methods for its determination depending on extraction with dilute acids have been proposed.

The Dyer citric acid method was also used for many years for the determination of available potash (K_2O) in the soil. Using this method of extraction, figures below 0·01 per cent. may be regarded as low and figures above 0·02 per cent. as high. More recently, extraction with acetic acid has been used. The figures thus obtained are not greatly different from those obtained by the Dyer method and approximate to the exchangeable potash figure. If it were desired to obtain the exchangeable potash it would be necessary to leach the soil with dilute acetic acid or ammonium acetate until no more potash comes into solution. The following standards may be used for ordinary British agricultural soils :

	mg. K_2O per cent.
Very low	0–3
Low	4–6
Medium low	7–9
Medium	10–12
Medium high	12–18
High	19 +

The total potash in the soil can be determined by a fusion method. Actually, this determination is rarely carried out, because the figures obtained are of little significance in indicating the availability of potash in the soil. Most of the potash is in the form of unweathered minerals, such as felspars and ferromagnesian minerals and is of little immediate importance for plant nutrition. It was formerly the practice to determine the potash soluble in 20 per cent. HCl after 48 hours' digestion at 100° C. This figure, referred to as "total potash" was supposed to indicate the amount of potash present as a reserve in the soil. In ordinary British soils the figures by this method vary from about 0·2 per cent. in light sandy soils to over 1·0 per cent. in heavy and fine silty soils.

Determination of Base-status

By determination of base-status we understand any determination or determinations which have as their object answering the questions : (1) is the soil in need of applications of lime, and (2) if so, how much lime must be applied ? The answers to these questions may be sought by a variety of methods, some depending on measurements of the acidity of the soil and others depending on determining the amount of lime present in an available form.

Before discussing these methods it will be convenient to recall the essential features of the acid-base equilibrium in soils. It has been shown in Chapter VII that the reactive complex of the soil is actually or potentially acid in character. In neutral or alkaline soils the acidity is neutralized by bases, principally calcium, and any excess of base over and above that needed to neutralize the soil acids is present in the form of carbonates, mainly calcium carbonate.

Most of the methods in actual use for determining the base-status of soils seek to find some measure of their acidity. The most popular of these determinations, possibly on account of the ease with which large numbers can be dealt with for routine purposes, is the determination of *p*H.

According to commonly accepted theory, acids dissociate in solution giving hydrogen-ions and the associated anions. For example, a dilute solution of hydrochloric acid is supposed to be dissociated into positively charged hydrogen-ions and negatively charged chloride-ions. This dissociation is almost complete in dilute solutions of the so-called strong acids such as hydrochloric, nitric, and sulphuric acids. Weak acids are only slightly dissociated. Thus, a decinormal solution of hydrochloric acid has a hydrogen-ion concentration of nearly 0·1 g. per litre, whilst a decinormal solution of a weak acid, acetic acid, has a hydrogen-ion concentration of only 0·0013 g. per litre. The hydrogen-ion concentration is, so to speak, a measure of the intensity of acidity. The relation of hydrogen-ion concentration to *p*H is seen from the following table :

Hydrogen-ion Concentration.	*p*H
0·1	1·0
0·01	2·0
0·001	3·0
0·0001	4·0

*p*H is thus the negative logarithm of the hydrogen-ion concentration.

Neutrality is represented by *p*H 7·0, the hydrogen-ion concentration of pure water being 10^{-7}. *p*H values less than 7·0 represent acidity and *p*H values greater than 7·0 alkalinity. The acids present in the soil are weak and insoluble. Thus, both on account of their low solubility and their low degree of dissociation, the aqueous solutions in equilibrium with them have very low hydrogen-ion concentrations. It is exceptional to find aqueous suspensions of soils, even when deprived of exchangeable bases, with *p*H values below 4·0, i.e., with hydrogen-ion concentrations greater than 10^{-4}. Values below *p*H 4·0 usually indicate the presence of small amounts of mineral acids such as sulphuric acid.

When we speak of the *p*H of a soil we mean usually the *p*H of the soil in aqueous suspension. It should be noted, however, that the actual *p*H will vary according to the ratio of soil to water, and generally falls as the ratio becomes narrower. The *p*H of a watery suspension of a soil may thus be considerably higher than the *p*H of the soil moisture under field conditions.

The determination of *p*H may be carried out by an electrometrical method. Several types of electrodes are available and one of these methods should be used for accurate results. For more approximate purposes, use may be made of coloured indicator solutions that change colour at certain *p*H values. The following are typical indicators, with their corresponding colour changes :

Indicator.	*Colour Change.*	*p*H *Range.*
Bromo-phenol blue . .	Yellow–blue	2·8–4·6
Bromo-cresol green . .	Green–blue	3·6–5·2
Bromo-cresol purple . .	Yellow–purple	5·2–6·8
Bromo-thymol blue . .	Yellow–blue	6·0–7·6
Cresol-red	Yellow–red	7·2–8·8

The actual determination may be made on the filtered or centrifuged aqueous extract of the soils A more convenient method, sufficiently accurate for a field test, is to shake up the soil with a standard mixed indicator, e.g. the B.D.H. universal indicator, which gives a range varying from blue for *p*H 7·5, through green, yellow, and orange, to red at *p*H 4·0. The test is carried out in a small porcelain dish divided into two compartments into one of which a small amount of soil is placed and covered with the indicator. After mixing and standing, the indicator is run off into the other compartment and the colour noted.

The determination of the *p*H of the soil by colorimetric methods, whilst useful for giving an approximate idea in the field, is not accurate enough for advisory purposes and still less for research purposes. It is therefore usual to determine it in the laboratory by an electrometric method. The use of these more accurate methods should not, however, allow us to overlook some of the inherent difficulties both in the determination and in the interpretation of *p*H.

In the first place, in electrometric methods, it is usual to determine the *p*H of the soil in aqueous suspension, a conventional ratio being one of soil to 2½ parts of water. The determination of *p*H at the moisture contents usually occurring in the field is not easy, but recent American work has shown that there is a general tendency for the *p*H to fall with moisture content. This means that at ordinary field moisture contents, the *p*H is less than that determined in the laboratory on a watery suspension and that as the soil dries out, even lower *p*H values may obtain.

The second difficulty in determining the *p*H of the soil is that it is liable to fluctuations throughout the season. This variation may amount to as much as one *p*H unit, the higher figures being generally obtained at the end of the winter.

From these considerations it is evident that *p*H as determined in the laboratory is only an approximate indication of the true *p*H of the soil in the field in the vicinity of the roots of plants, and that even this *p*H is subject to variation during the course of the year. We cannot regard the *p*H of the soil, as ordinarily determined, as being a definite figure such as the percentage of nitrogen, carbon, or exchangeable calcium in the soil. To say that the *p*H of the soil is 6·0 is meaningless unless precise conditions of sampling and determination are specified. Any correlations between *p*H and optimum growth of crops must necessarily be very approximate and this must apply also to estimates of critical *p*H values below which certain crops will not grow satisfactorily. It is possible that better correlations would be obtained if the *p*H determinations were made under actual field conditions during the period of growth of the crops in question.

In ordinary routine advisory work, *p*H determinations are usually made with the object of ascertaining whether the soil is sufficiently acid to require lime dressings. To this procedure there can be no objection, but it would be dangerous to use *p*H as a basis for assessing the actual rates of dressings.

The most widely used method in this country for assessing the amount of lime needed by soils is the Hutchinson-MacLennan method, in which the soil is shaken with a standard (about N/50) solution of calcium hydrogen carbonate. With an acid soil a reaction takes place, whereby the calcium hydrogen carbonate is decomposed with liberation of carbon dioxide. By comparing the titre of the original solution with that of the filtrate after reaction has taken place, the amount of acidity is estimated and converted into terms of calcium carbonate required for neutralization. Since one acre of soil down to ordinary tillage depth weighs about 1,000 tons, 0·1 $CaCO_3$ requirement means 1 ton per acre. The method is fairly satisfactory for most English soils but is untrustworthy for soils rich in organic matter.

Another class of methods for determining lime requirements depends essentially on titrating the soil to a certain *p*H, generally 6·5 or 7·0. Varying amounts of an alkaline solution, e.g. baryta, are added to portions of the soil and after allowing time for reaction, the *p*H is determined in each lot. From the curve connecting the *p*H found with the amount of baryta added the equivalent amount of lime or calcium carbonate needed to bring the soil to 6·5 or 7·0 may be deduced. The object of this type of method is to discover what amount of lime or limestone is required to raise the *p*H of the soil to a certain *p*H in the field. Apart from the uncertainty as to what constitutes the optimum *p*H, it is found that considerably larger amounts than those indicated in the laboratory are required in practice to give the desired *p*H. It is therefore necessary to introduce a " liming factor " as a correction. In some cases this may be as much as 3, i.e., the requirement found in the laboratory must be multiplied by 3 to give the field dressing.

Another group of methods depend on the determination of available lime in the soil. Methods have been proposed for determining the amount of lime soluble in water, or in dilute solutions of carbon dioxide, but the most widely used method of this class is the determination of exchangeable calcium. For average soils, figures less than 0·2 per cent. exchangeable CaO indicate deficiency. As with other types, methods of assessing lime requirement based on the determination of exchangeable calcium must be correlated with field experience.

For example, in North Wales 0·30 per cent. exchangeable CaO is found to be a satisfactory figure for medium soils. Thus 0·10 per cent. exchangeable CaO indicates a deficit of 2 tons CaO per acre, assuming the weight of an acre of soil to cultivation depth to be 1,000 tons. For other conditions, other standards might be used. For light soils, a figure of 0·20 per cent. CaO would be satisfactory.

Before leaving the question of the determination of the acid-base status of soils, some observations on the use of the term " lime requirement " seem desirable. Although it is often said that the agricultural chemist determines the lime requirement of a soil, this is not an exact statement. The analyst actually either determines some property depending on the acidity, as, for example, the amount of base required to bring the soil to a *p*H of 7·0 under certain conditions, or else determines a certain category of base, e.g., exchangeable calcium. From his estimate of acidity in the first case or from his estimate of basicity in the second case, he infers what dressing of lime or limestone should be given in the field for the particular type of agricultural practice. A correlation with practical experience is therefore implied. Unfortunately, not nearly enough careful field experiments have been carried out and, therefore, even the most refined laboratory determinations may be of comparatively little value if the necessary experience for correlating them with practice is lacking. On the other hand, almost any method if backed by local experience can be interpreted with reasonable success and, therefore, in spite of the diversity of methods in use, soil analysis for the purpose of making recommendations on liming achieves a fair measure of success.

Soil Analysis by the Plant

So uncertain are the conclusions to be drawn from the chemical analysis of the soil that new methods are now being employed for the estimation of the fertilizer requirements of a soil based upon the growth of a test plant in the soil. Two experimental methods have been worked out, by Mitscherlich of Königsberg and by Neubauer of Tharandt; in both methods the conclusions are drawn from plants grown in samples of the soil under regulated conditions, not from plants growing in the field.

Mitscherlich's method depends on the hypothesis that each of the main fertilizing constituents—nitrogen, phosphoric acid, and potash, exerts an action on the plant, independently of the others, that is measurable by the dry matter produced. With successive additions of the constituent to the soil there will be increases of dry matter produced at a diminishing rate until a maximum is reached, which maximum is a constant for that constituent though its actual value depends upon the condition of the soil as regards all the other factors of growth. Confining our attention to the one constituent, the ratio of the yield obtained from a particular soil to the yield obtained when the constituent has been added up to the optimum, will represent some specific and invariable ratio (not necessarily the same ratio) which the amount of the constituent available in the soil bears to the optimum amount. E.g., if the soil without any potash yields 20 per cent. less than the soil fully supplied with potash, then the untreated soil only contains one-half of the optimum amount of the constituent that has been added. In this illustration the one-half is a hypothetical figure; the actual ratios corresponding to differences of yield have to be determined by experiment but are true of all soils. The experimental procedure consists in growing oats in specially designed pots holding about 6 kilos of equal parts of the soil and coarse sand. Sixteen pots are required, which provide a fourfold repetition of each treatment: (1) complete fertilizer, (2) potash and phosphoric acid but no nitrogen, (3) potash and nitrogen but no phosphoric acid,

(4) nitrogen and phosphoric acid but no potash. The quantities of each fertilizer added are sufficient for maximum growth. Fifty grains of oats are sown in each pot, the number of plants being afterwards reduced to thirty-five. A preliminary determination is made of the water-holding capacity of the soil-sand mixture, and at starting, the water content is adjusted to something less than full capacity. The pots are weighed from time to time when growth has begun to produce a difference in the water content. Each pot is maintained at full capacity until a short time before the maturity of the grain, when watering is discontinued in order to promote ripening. Finally the grain and straw produced are harvested separately and their dry weights determined.

From these results it is possible to state the amounts of available nitrogen, phosphoric acid, and potash in the soil and the relation these bear to the optimum amounts. Further conclusions can be drawn as to the quantity of each fertilizer that can profitably be applied to the soil. From this brief account it will be seen that the technique of the Mitscherlich method is elaborate and the time required is considerable, not less than one growing season.

The results, however, are of permanent value for the particular soil, because recommendations can be deduced from the results that will cover not merely the next crop but the year by year manurial management of the soil. A large amount of work has been done by this method in Prussia and though the hypothesis on which it is based has been subject to much criticism, the results are so far in accord with those obtained from experimental plot work and practice, that no less than six experimental stations are at work in order to provide for the examination of soils in Prussia. In essence the Mitscherlich method aims at summing up the amounts of the available fertilizer constituents in the soil, from which can be calculated the balance of these constituents that would be appropriate to each crop.

The Neubauer method proceeds upon a different principle and attempts to estimate the available phosphoric acid and potash in the soil by determining the amounts of these constituents taken up by young seedlings of rye. The sample of soil taken in the usual way is allowed to become air-dry and then passed through the 2 mm. sieve. 100 grams of the fine earth are mixed with 50 grams of a pure sand and placed at the bottom of a glass cylinder 7 cm. high and 11 cm. in diameter. This soil mixture is covered with 250 grams of pure glass sand moistened with 80 c.c. of water. 100 grains of rye, which have been weighed and sterilized, are planted symmetrically in the surface layer of sand. A glass tube is thrust through the sand down to the soil layer for subsequent watering purposes, then the pots are covered with a glass plate and weighed. They are put into a constant temperature chamber at 20° to germinate and kept there until the shoots reach the glass cover, which is then removed. Seventeen days' growth is then allowed, the moisture content being adjusted each day after weighing, for ten days at the original 80 c.c. per dish, afterwards at 100 c.c.

Finally, on the eighteenth day the growing material is removed, the roots are washed free of soil and sand, and the whole is dried and gently incinerated. In the ash the potash and phosphoric acid are determined by the usual methods. A blank experiment is necessary in which the rye is grown in sand only, in order to obtain the datum line from which the potash and phosphoric acid taken up by the seedlings from the soil can be estimated. According to Neubauer the "limiting values" for soils which contain enough of the mineral constituents to give optimum crops, are represented by an absorption by the seedlings of 24 mgrms. K_2O and 6 mgrms. P_2O_5. The condition of the soil under examination may then be estimated by the extent to which the seedlings grown upon it fall short of these values.

Neubauer's method is obviously empirical and is probably subject to improvement both in the choice of the test plant and the standardization of the seed. But it is comparatively simple and rapid in execution, and the results do represent something comparable with the growth of the crop in the soil. Extensive comparisons have been made in Germany between the results of field experiments and the Neubauer tests of the soils, and the correlation is satisfactory, the disagreement being only of the same order as the probable error of the field trials. The method is worthy of careful investigation in this country as it promises to be more useful than any other to the adviser on soils and fertilizers.

An entirely different approach to the problem of determining the plant nutrient status of soils is to use the soil as a constituent of a culture medium for the growth of a mould, *Aspergillus niger.* Soil is mixed with a solution containing citric acid and other nutrients, omitting either potassium or phosphorus. The weight of mycelium found after inoculation with mould spores and a suitable period of incubation, gives an index of the plant nutrient status. In effect, this type of method is essentially a laboratory variant of the pot or plot method, the difference being that the yield of mycelium is measured instead of the yield of a standard crop plant. This class of method has its advocates, but it is somewhat laborious to carry out and it would still be necessary to standardize the results against field experience.

Leaf Diagnosis of Nutrient Deficiencies

In the diagnosis of plant nutrient deficiencies in the field considerable use may be made of leaf symptoms. For example, lack of potassium in cereals is shown by spotted or intervenal chlososis of the leaves, with scorching at the tips and from the edges inwards. Characteristic potash symptoms are seen also on other plants and trees. Purple colouring in the leaves of young cereals indicates phosphate deficiency. Boron deficiency in swedes, kale, and mangolds is shown by characteristic brown internal rots of stems and roots. Considerable experience is necessary for the accurate diagnosis of nutrient deficiencies from symptoms on growing crops. As an introductory guide to the subject, Professor Wallace's *Diagnosis of Mineral Deficiencies in Plants,* which includes a colour atlas of symptoms, may be profitably consulted.

Uses and Limitations of Soil Analysis

In the present state of our knowledge, it is impossible from an analysis of the soil to say in every case what nutrients are deficient and how much of each should be given in the form of manures or fertilizers. Present procedures in soil analysis have developed in different countries and even in different parts of our own country in response to the needs of practice. Most of the methods used give fairly satisfactory results when used in the light of local experience. It is realized that many of the methods lack a firm scientific foundation, yet so long as they meet practical needs fairly well, they are used in preference to new and untried methods. It is yet of the highest importance to replace these empirical methods by better methods and much work is needed to this end.

It may be of interest to consider what would be the ideal procedure if it were found necessary to devise an analytical method for an element, not hitherto determined in the ordinary routine. Let us suppose that experiments have shown that element X is necessary for plant growth and that it might occasionally be deficient in the soil.

It would be realized at the outset that, although a determination of the total amount present might give an approximate idea of the position, it would be necessary to distinguish between available and unavailable X. This would entail an investigation of the forms in which X occurs in soils. It might be found that there were three categories, namely, water-soluble X, exchangeable X, and X in the form of unweathered minerals. The next step would be to carry out a large number of determinations on different types of soils to discover what constitutes normality, what excess, and what deficiency of the element in the different categories. An attempt would then be made to correlate these figures with field behaviour. As a first step a comparison might be made of soils responsive and soils unresponsive to manuring with X. In this way an idea would be obtained as to what, in terms of soil analysis, constitutes X deficiency.

The final step would be the laying down of careful field experiments to determine the response by different crops under different soil and climatic conditions to varying doses of X applied as dressings. Comparing these responses with the analytical results obtained with the different soils, standards would be obtained for assessing the need for X manuring for each crop.

Such a programme would involve a considerable amount of work in field and laboratory. Our existing standards for assessing the status of the soil with respect to the commoner manurial constituents, nitrogen, phosphate, potash, and lime still lack a satisfactory basis, such as has been outlined as ideal for the hypothetical manurial ingredient X. Yet, in practice, backed by the accumulation of years of local experience, they do prove of considerable value ; and until improved methods and more trustworthy standards are devised they cannot lightly be abandoned.

To the pure chemist, it may appear unsatisfactory that agricultural chemists in different parts of such a small country as our own should be using different methods of soil analysis. It would, of course, be desirable to have one standard system of soil analysis, but even if such a system had been devised, it would still be necessary to use different standards or even different extractants for different soil and climatic conditions. Thus whilst the citric acid method for determining available phosphoric acid is fairly satisfactory for the arable soils of the south and east of England, extraction with acetic soil has given results better in accord with field experience in the humid grassland regions of North Wales.

APPENDIX I

A SELECTED BIBLIOGRAPHY

THE following books may be recommended to those wishing to pursue the subject to a more advanced stage :

E. W. HILGARD.—*Soils.* Macmillan Co., New York. A classical work by one of the pioneers in the study of the soil.

E. Ramann.—*Bodenkunde.* Julius Springer, Berlin. Also a classical work, written from the purely scientific standpoint.

E. J. Russell.—*Soil Conditions and Plant Growth.* Longmans, Green, & Co., London. A standard textbook with a very copious bibliography.

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Proceedings of the Soil Science Society of America.—Published by the Society at Morgantown, W.Va.

Soil Research.—Published by the International Society of Soil Science. At present suspended.

APPENDIX II

EXAMPLES OF PROFILE DATA

Locality.—Churn Hill, Upton, Berks.
Soil Series.—Upton.
Geology.—Middle Chalk.

ANALYSIS OF AIR-DRY 2 mm. SAMPLE

	0–4½″	*4½–12½″*
Coarse Sand	4·9	4·1
Fine Sand	23·6	22·1
Silt	3·5	7·3
Clay	18·6	20·7
Moisture	3·3	3·2
Calcium Carbonate	43·3	41·5
Loss on Ignition	8·5	6·3
Organic Matter	4·5	2·4
*p*H	8·3	8·4
Exch. CaO	—	—
Total P_2O_5	0·20	0·06

CLAY FRACTION

SiO_2/Al_2O_3	2·68	—
SiO_2/R_2O_3	2·16	—
Al_2O_3/Fe_2O_3	4·15	—

FIELD DESCRIPTION

Topography.—Undulating, elevated.
Vegetation.—Seeds, ley.
Profile.—0–4½″ Buff calcareous light loam, loose. 4½–12½″ Pale brown light loam with abundant chalk fragments, increasing in size with depth. Chalk rock at about 12½″.

Locality.—Denchworth, Berks.
Soil Series.—Denchworth.
Geology.—Mainly Kimmeridge Clay with some alluvium.

ANALYSIS OF AIR-DRY 2 mm. SAMPLE

	0–8″	*8–18″*	*18–40″*	*40–48″*
Coarse Sand . .	2·25	2·3	3·4	0·3
Fine Sand . .	25·1	27·7	28·6	35·25
Silt . . .	17·0	14·0	20·0	21·75
Clay . . .	39·0	47·2	45·35	41·4
Moisture . .	8·9	6·85	7·45	6·3
Calcium Carbonate .	Nil	Nil	Nil	2·1
Loss on Ignition .	14·6	8·6	6·3	5·5
Organic Matter .	9·9	3·65	1·5	0·6
*p*H . . .	4·6	4·3	5·4	7·4
Exch. CaO . .	0·72	0·58	0·53	0·62
Total P_2O_5 . .	0·15	0·10	0·13	0·11

CLAY FRACTION

SiO_2/Al_2O_3 . .	3·70	3·55	3·55	3·69
SiO_2/R_2O_3 . .	2·98	2·84	2·71	2·90
Al_2O_3/Fe_2O_3 . .	4·14	4·00	3·23	3·80

FIELD DESCRIPTION

Topography.—Flat and depressed.
Vegetation.—Old rough pasture.
Profile.—0–8″ Grey heavy clay loam, strongly rust-mottled ; crumb structure, loose. 8–18″ Grey clay, strongly orange-mottled ; fairly stiff ; prosmatic structure. 18–40″ Grey clay, very strongly bright orange-mottled ; very stiff and tenacious, prismatic structure. 40–48″ Grey mottled khaki, containing small white calcareous particles.

Locality.—Mynydd Rhiw, Caernarvonshire.
Series.—Rhiw.
Geological Data.—Colluvium derived from quartz dolerite.

ANALYSIS OF AIR-DRY 2mm. SAMPLE

	0–6″	*6–12″*	*12–17″*
Coarse Sand	11·5	27·8	39·3
Fine Sand	33·6	33·5	40·3
Silt	15·3	14·5	12·0
Clay	19·0	14·5	6·5
Moisture	5·1	4·1	2·6
Calcium Carbonate	Nil	Nil	Nil
Loss on Ignition	21·0	11·6	6·2
Organic Matter	19·3	8·9	2·7
*p*H	5·1	5·1	5·25
Exch. CaO	0·08	0·045	0·02
Total P_2O_5	0·193	0·140	0·113
Stones in bulk sample	10·0	33·7	45·2

CLAY FRACTION

SiO_2/Al_2O_3	2·87	2·44	2·00
SiO_2/R_2O_3	1·87	1·44	1·27
Al_2O_3/Fe_2O_3	1·87	1·44	1·74

FIELD DESCRIPTION

Topography.—Boulder-strewn scree slope. Rock pavement in places; soil pockety.

Drainage.—Good.

Vegetation.—Grassy heath with heather (tetralix) and gorse (Gallii) dominant in places. Fair amount of wild white clover.

Profile.—0–6″ Dark brown peaty loam. 6–12″ Brown, slightly peaty, stony loam. 12–17″ Yellowish cinnamon-brown, brashy light loam.

Locality.—Ty'n-y-coed, Abersoch, Caernarvonshire.
Series.—Penrhyn.
Geological Data.—Ordovician Shale.

ANALYSIS OF AIR-DRY 2mm. SAMPLE

	0–4½"	*4½–9"*	*9–13"*	*13–20"*
Coarse Sand . .	18·6	17·2	16·7	29·4
Fine Sand . .	23·7	25·2	31·9	42·9
Silt . . .	20·8	22·0	23·2	17·0
Clay . . .	25·3	27·3	22·8	9·6
Moisture. . .	3·5	3·0	2·4	1·3
Calcium Carbonate .	Nil	Nil	Nil	Nil
Loss on ignition .	11·3	9·2	6·9	5·1
Organic Matter .	6·6	4·1	2·4	0·6
*p*H . . .	5·2	5·0	5·0	5·1
Exch. CaO . .	0·12	0·105	0·09	0·05
Total P_2O_5 . .	0·241	0·213	0·158	0·087
Stones in bulk sample	2·8	11·9	14·6	29·3

CLAY FRACTION

SiO_2/Al_2O_3 . .	2·39	2·37	2·38	2·47
SiO_2/R_2O_3 . .	1·94	1·92	1·91	2·06
Al_2O_3/Fe_2O_3 . .	4·31	4·27	4·07	5·02

FIELD DESCRIPTION

Topography.—Very slight slope.
Drainage.—Good.
Vegetation.—Old pasture of inferior composition.
Profile.—0–4½" Dark, slightly greyish-brown medium loam. 4½–9" Brown, slightly stony (entirely shale) medium loam. 9–13" Slightly yellowish-brown, slightly stony medium loam. 13–30" (on rock) Pale grey-brown stony (shale) medium loam with very fine shale.

Locality.—Bodvel, Llannor, Caernarvonshire.
Series.—Eivion.
Geological Data.—Boulder Clay derived from igneous rocks.

ANALYSIS OF AIR-DRY 2mm. SAMPLE

	0–6″	*6–12″*	*12–17″*	*20–26″*
Coarse Sand . .	8·9	9·6	5·9	6·7
Fine Sand . .	29·9	32·0	27·1	24·6
Silt . . .	26·8	27·8	29·3	30·3
Clay . . .	22·4	22·8	33·4	33·6
Moisture. . .	3·4	2·6	2·1	2·7
Calcium Carbonate .	Nil	Nil	Nil	Nil
Loss on ignition .	12·4	7·8	4·5	5·3
Organic Matter .	9·8	5·0	0·8	1·7
*p*H . . .	4·55	4·7	4·7	5·7
Exch. CaO . .	0·05	0·07	0·105	0·17
Total P_2O_5 . .	0·130	0·125	0·043	0·048
Stones in bulk sample	n.d.	n.d.	n.d.	n.d.

CLAY FRACTION

SiO_2/Al_2O_3 . .	2·69	2·42	2·64	2·38
SiO_2/R_2O_3 . .	2·13	1·99	1·93	1·72
Al_2O_3/Fe_2O_3 . .	3·83	4·63	3·63	2·49

FIELD DESCRIPTION

Topography.—Slight slope.
Drainage.—Impeded.
Vegetation.—Fair pasture with rushes.
Profile.—0–6″ Dark grey-brown, heavily mottled silt loam. 6–12″ Slightly paler, heavy silt loam; heavily mottled. 12–24″ Pale variegated greyish-yellow-browns, having appearance of marblings; silt clay. 24″ + Slightly greyer and stiffer; silt clay. Profile generally stoneless excepting occasional large boulders.

Locality.—Bronheulog, Ceidio, Caernarvonshire.
Series.—Bodvel.
Geological Data.—Glacial sand of Carboniferous origin.

ANALYSIS OF AIR-DRY 2mm. SAMPLE

	0–5″	*5–10″*	*10–15″*	*15–27″*	*27–37″*	*37″ +*
Coarse Sand .	18·8	20·4	9·8	1·0	9·6	21·6
Fine Sand . .	60·0	59·5	75·8	88·7	80·5	74·5
Silt . . .	9·2	10·2	5·8	11·2	8·8	3·3
Clay . . .	7·0	6·3	5·8	Trace	2·3	0·3
Moisture . .	1·3	1·0	0·7	0·5	0·6	0·3
Calcium Carbonate	Nil	Nil	Nil	Nil	Nil	Nil
Loss on ignition .	5·6	3·8	2·3	1·7	1·3	1·0
Organic Matter .	4·6	2·2	0·7	0·3	0·2	0·1
*p*H . . .	4·9	5·0	5·4	5·3	5·7	5·7
Exch. CaO . .	0·03	0·03	0·03	0·02	0·03	0·02
Total P_2O_5 . .	0·118	0·094	0·052	0·034	0·037	0·044
Stones in bulk sample . .	Nil	Nil	Nil	Nil	Nil	Nil

CLAY FRACTION

SiO_2/Al_2O_3 .	2·81	2·48	2·36	1·83	2·52	2·41
SiO_2/R_2O_3 .	2·09	1·85	1·82	1·50	1·99	1·87
Al_2O_3/Fe_2O_3 .	2·90	3·00	3·37	4·50	3·76	3·47

FIELD DESCRIPTION

Topography.—Sharply undulating.
Drainage.—Very free liable to drought.
Vegetation.—Poor pasture.
Profile.—0–5″ Greyish-brown fibrous loamy sand; occasional well rounded pebbles. 5–10″ Brown, essentially similar in texture; stoneless. 10–15″ Light brown fine sand; stoneless. 15–27″ Pale grey-brown fine sand; stoneless. 27–37″ Pale grey-brown with cemented clods of dark reddish-brown, stoneless, fine sand. 37″ + Pale grey-brown fine sand; stoneless.

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